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M. R. Brininstool

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OCEANIC APPLICATIONS OF FIBER OPTICS

Michael R. Brininstool

Naval Ocean Syst Center
Ocean Engineering Division
San Diego, CA 92152

ABSTRACT

Oceanic applications of fiber optics are rapidly advancing, following on the heels of the more mature land-based telecommunications systems. While many features of each arena are similar, undersea fiber systems demand unique capabilities. Components capable of withstanding brutal hydrostatic pressures and near freezing temperatures had to be developed. This paper highlights undersea fiber optic systems and their features. It focuses on long distance telecommunications and remotely-operated-vehicle (ROV) links. Also addressed is the emerging technology of fiber optic sensors. These designs use the fiber as a sensing element to detect such variables as displacement, pressure, temperature, strain, and rotation.

INTRODUCTION

Fiber optics is increasingly becoming the media of choice in a wide assortment of undersea applications. The main thrust of development efforts are directed toward fiber optic telemetry and sensors. Several distinct advantages over conventional wire technology are exploited. Fibers possess very low intrinsic attenuation of the optical power traveling down the waveguide. With the common silica-glass based fiber used today, attenuations as low as 0.2 dB/km are achievable. This compares dramatically to coaxial transmission lines where the attenuation varies as a function of carrier frequency and can range from 4 to 100 dB/km for moderate bandwidths of 100 MHz.

Optical fibers have extremely large bandwidth-length products. The single-mode fibers, at the high performance end of the fiber product line, have bandwidth-length products as high as 800 GHz-km. Even the more modest multimode fibers can provide 1 GHz-km. These values translate into huge bandwidth-limited transmission distances. However, for most applications, it is the fiber attenuation, not the bandwidth that usually limits the ultimate distance a signal can be transmitted. For trans-oceanic communications links, the attenuation-limited distance determines how many repeaters are required and thus directly influences the system cost. The latest fiber optic transatlantic link was brought on-line in November 1989. Known as TAT-8, the 6100-km system bridges the east coast of the United States to Great Britain and France with a telephone system capable of simultaneously transmitting 40,000 digitized voice channels at a data rate of 280 Mbps [1]. The system requires only 125 repeaters, spaced 50 km apart. Future systems will be able to extend that spacing to 100-150 km. TAT-7 was the last transatlantic coaxial cable system placed in service. In comparison, the repeater spacing was only about 10 km and the cable carried 4200 analog phone circuits.

Fiber optics will continue to play a large role in undersea links, increasing channel capacity and repeater spacing distance. Both of these improvements provide great cost savings. As the number of voice channels grows the cost per channel diminishes. The TAT-8 system cost $360 million, or $9,000 for each of its 40,000 voice lines. Capacity expansion by at least a factor of 20 is anticipated over the next five years. Each repeater cost about $800,000 for TAT-8. New optical amplifier technology aims at reducing both the number, complexity, and cost of a repeater while improving the reliability.

Small size and light weight are two other outstanding features optical fiber offers to undersea links. As an example, an expendable, underwater tether cable for ROV telemetry has a diameter of only 900 μm and weighs less than 1 kg/km in air and is nearly neutrally buoyant in water. A coaxial cable with comparable bandwidth is about 30 mm in diameter and weighs over 1110 kg/km. For ROVs, the size and weight savings means reduced cable drag, extended mission lifetime, and enhanced packing density of the spooled cable housed within the vehicle.

TELEMETRY APPLICATIONS

This section addresses a few applications of fiber optics applied to undersea telemetry. Included are long-haul systems and ROV communication links.

Long-Haul Systems

Most of the fiber deployed for long-haul trans-oceanic systems is used for carrying telephone channels. Shared on the telephone lines are facsimile and computer data and, to a growing extent, video transmission. AT&T is playing a significant role in installing trans-oceanic links. In addition to the TAT-8 system, another trans-Atlantic route, TAT-9, is expected to be completed in December 1991. Taking advantage of newer 1.55-μm laser technology, it will carry 80,000 voice channels over three 560-Mbps fiber pairs, with 100-km repeater spacings. Another route, TRANSPAC-3, or TPC-3, will run from Hawaii to Japan via Guam. All current designs use similar approaches. To achieve long repeater spacings the fiber link consists of long-wavelength high-powered laser-diode transmitters, low-loss single-mode optical fibers, and high-sensitivity PIN-FET receivers.

In addition to power budget considerations, it is also important that the fiber system maintain adequate bandwidth over the repeater span. Laser diodes have very high modulation bandwidths, with some capable of 10 GHz. The coherence of the laser aids in maximizing the fiber bandwidth. Its narrow spectral linewidth minimizes pulse spreading due

to chromatic dispersion in the fiber. The single-mode fiber bandwidth is virtually unlimited when used with optimized laser sources. Receiver bandwidth is kept close to the system bandwidth to reject out of band electronic noise. This optimizes the signal-to-noise ratio and the sensitivity.

Because the noise bandwidth influences receiver sensitivity, repeater spacings are dependent on the required data rate of the system. As the system data rate increases the span length decreases since more incident optical power is required at the receiver to overcome the noise. This is illustrated in Figure 1, plotting repeater spacing as a function of data rate for a fiber link comprised of a laser transmitter, a single-mode fiber, and a PIN-FET receiver. The two curves represent results from using two different values for optical safety margin. The safety margin insures against future link degradations due to laser output power reduction, increased fiber attenuation, and potential repairs. The margin is added to the total optical loss allocated for fiber attenuation, splice and connector loss, and other passive component losses incurred along the path. A 3-dB safety margin is considered minimal, especially for undersea applications and 10-dB margin is more practical. The TAT-8 system employs a 9-dB margin: 2 dB allowance for repair, 4 dB for laser ageing, and 3 dB for an end of life margin [2].

Figure 1 is used to quickly determine the maximum data rate capacity a fiber link can manage if the span distance is given. For example, supposed a repeaterless link is to be installed over 160 km, approximately 100 miles. For a 10-dB safety margin, the data rate limit is about 10 Mbps. This is equivalent to roughly 150 uncompressed voice channels. The figure can also be used conversely to determine repeater spacing for a link given the system data rate.

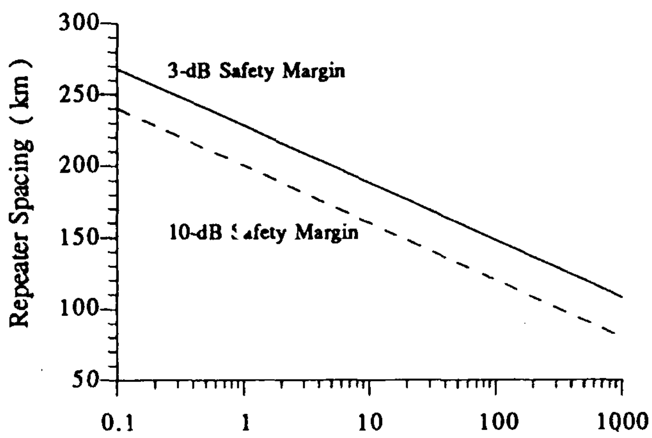

Figure 1. Repeater Spacing for Laser / Single-mode Fiber / PIN-FET Receiver Systems

The repeater for an undersea link houses the receiver, transmitter, power circuitry, and associated supervisory control electronics. The control electronics monitors the health of the repeater components and notifies a master supervisor of any trouble. For higher reliability, redundancy is used. The TAT-8 system uses six optical fibers in its cable. Two pairs are active and one pair is on standby. The repeater has three extra lasers that can be switched remotely by the master supervisor in the event of a laser and / or fiber failure. The repeater electronics are maintained at one atmosphere pressure. The housing seals around the ends of the cable terminations.

Submarine Cable

The underwater fiber optic cable must meet several stringent requirements to maintain the integrity of the fiber. The cable must protect the fiber from longitudinal stresses, moisture intrusion, large hydrostatic pressure exposure, and extreme thermal excursions.

The fiber element is fundamentally very strong. However, microscopic defects along the surface of the fiber weaken the element considerably. Adding to this problem is moisture. In the presence of stress and moisture, the flaws in the fiber surface grow, further weakening the fiber due to stress corrosion. If allowed to continue, the flaw will ultimately sever the fiber. Although the fiber used for undersea cables is typically much stronger than that used in terrestrial cable, it still must be protected. The fibers are normally embedded in a stiff, matrix material, such as Hytrel™, which forms a bonded unit. Units housing multiple fibers place the fibers in a helix around a central steel "king" wire. Any axial load applied to the unit is taken up first by the king wire. Kevlar™ is another strength member used commonly in cables. Additional strengthening is added depending on the expected loads the cable will undergo during installation and service.

The TAT-8 system uses two types of cables: one for deep water and one for shallow water service. The deep water cable has a layer of galvanized steel wires enclosing the fiber optic unit in a pressure tolerant "cage". A thin copper layer is welded around the steel layer. The copper is used to carry the electrical current necessary to power the repeaters. The combination of the copper and steel layer provides a water-tight pressure-tolerant chamber for the fibers. Since the cable is manufactured on the surface, the fibers remain at one atmosphere for the entire system lifetime. This pressure-tolerant chamber is vital to the survival of the fiber elements. It eliminates the water intrusion, thereby reducing stress corrosion problems. The steel wires also significantly increase the tensile strength of the cable.

The optical transmission integrity of the fibers is also well preserved. If exposed to high levels of hydrostatic pressure, the fiber unit will begin to buckle. This buckling attributes to microbending attenuation in the fibers. If severe, the fibers can go completely dark. The steel strength members prevent hydrostatic pressure from effecting the fiber unit. Under pressure the steel wires lock up, forming a rugged barrier. The copper layer serves as a water and hydrogen barrier. Hydrogen, from filling compounds in the cable, has been shown to diffuse into the fiber increasing optical transmission losses due to absorption.

Thermal-induced contractions in the fiber unit at low temperatures can also cause microbend attenuation. This contraction is restricted by the helix within the Hytrel™ matrix and by the steel strength members. Surrounding the

strength members is a thick layer of low density polyethylene. This layer serves as the insulation for the electrical current. A sea-water ground return is used and the current must be isolated.

The shallow water cable has thick galvanized steel armor wires surrounding the deep water cable structure. This armoring protects the cable against accidental fishing trawler damage and abrasion caused by continual movement across coral and rocks.

The Future of Long Haul

There are several exciting technologies emerging that promise great improvements for long-haul undersea links. They are aimed at extending the repeater spacing and channel data rate capacity. Four significant technologies discussed here are mid-infrared fiber optics, coherent fiber optics, optical fiber amplifiers, and soliton communications.

The TAT-8 system uses fiber made from silica glass and transmits data over the fiber with laser diodes emitting in the 1.3-μm wavelength range. This wavelength was chosen because it corresponds to a low-attenuation, low-dispersion window in silica glass. Also the 1.3-μm laser technology was the most mature at the time of development. Since then the 1.55-μm wavelength has become the color of choice. The glass exhibits a lower attenuation at 1.55 μm than at 1.3 μm and thus data can be sent further. To maintain the high bandwidth requirement, fiber with the minimum dispersion wavelength shifted to 1.55 μm is used. Figure 1 was generated based on a 1.55-μm laser transmitter. This represents the wavelength for the lowest attenuation, 0.2 dB/km, attainable using silica-based glass. New types of fiber made from heavy-metal fluoride glass are being developed. When used at wavelengths of 2.7 μm, these fibers have the potential for attenuations as low as 0.001 dB/km [3]. Researchers at the Naval Research Lab, AT&T, and Corning have independently achieved losses of 1 dB/km, down from 20 dB/km just four years ago [4]. The rapid improvements are attributable to applying the lessons learned in making low-loss silica fiber over the last twenty years. Many obstacles must still be overcome. Suitable sources and detectors must be developed to operate in the mid-infrared region. Detectors must be cryogenically cooled to achieve high sensitivities due to thermal-generated noise currents in the detector at these wavelengths. The fiber material has low strength and a low melting temperature compared to silica. Fluoride glass has a very low melting temperature, 300 °C, compared to over 1000 °C for silica. The fluoride tends to be hygroscopic and readily absorbs water.

Presently, all undersea long-haul fiber systems use intensity modulation (IM) of the lasers to transmit digital data. Direct detection (DD) of the signals converts the intensity into electrical current. Coherent fiber optic communication systems (COFOCS) utilize the coherent nature of spectrally pure, single-longitudinal mode lasers. Information is impressed on the phase of the lightwave instead of the intensity, as is done with direct-detection systems. At the receiver, optical heterodyne mixing of the signal with a local optical oscillator provides improved sensitivities close to the quantum limit. Improvements in sensitivity of 5 - 20 dB can be achieved over direct detection schemes [5]. This translates into detecting weaker signals and being able to extend the repeater spacing distance. Receiver channel selectivity is another benefit COFOCS provides. More channels can be packed together on a single fiber line by separating them at slightly different optical frequencies, thereby increasing the ultimate bandwidth capacity of the fiber. Many technical issues are being addressed with COFOCS. The heterodyne receiver is very sensitive to the polarization state of both the local oscillator and the signal fields. Random phase fluctuations of the transmitter also cause degraded reception.

Probably the most publicized technical advance for extending repeater distance is in the area of optical fiber amplifiers. Fiber amplifiers are inserted directly into the optical path and provide gain to the signal. A coil of fiber, typically 10-100 meters long, is lightly doped with trivalent rare-earth ions such as erbium. The fiber coil is then excited with a laser-diode pump source using a WDM to couple the pump power into the coil. The pump power raises the rare-earth ions in the fiber coil to an excited metastable state of population inversion. Under this condition, according to quantum electronics, a signal passing through the coil with a wavelength equivalent to the transition between excited and ground states experiences a net gain due to stimulated emission. The principles are similar to gain developed in optically pumped lasers. Fiber amplifiers have many outstanding features. The fiber geometry offers unique advantages. The fiber is easily interfaced to the transmission line fiber. Fusion splices give low-loss, low-reflection coupling. The pump and signal powers are confined to a very small core area over an extended interaction length. This provides for efficient pump absorption over long lengths. The fiber gain is polarization insensitive. Fiber amplifiers are potentially more reliable and smaller than their opto-electronic counterparts. Unlike opto-electronic repeaters, the fiber amplifiers are essentially bit rate transparent. Experiments have shown a limit in the Tbps range [6]. Limitations in long-distance systems with multi-repeater fiber amplifiers include optical noise build-up as the light passes through the amplifier cascade chain and fiber dispersion which limits the data rate capacity.

The future will see rapid advances in gain performance and packaging of fiber amplifiers as they become widely adopted for an assortment of long-distance, multi-access distribution network, and sensor applications. One recent report stated fiber amplifier repeater gains of 55 dB were achieved. The fiber amplifier was employed in a laboratory IM/DD system and a 1.8-Gbps nonrepeatered transmission over a length of 308 km was accomplished [7]. Long-distance links employing both coherent detection and fiber amplifiers have been reported. One experiment at AT&T achieved 1.7-Gbps transmission over 419 km using an FSK coherent system with fiber amplifiers [8].

Communications experiments utilizing the physics of optical solitons are being conducted. As fiber amplifiers help to extend the power-limited distances for undersea links, the systems become bandwidth or dispersion-limited. The

narrow optical pulses spread into each other and become indistinguishable after many hundreds of kilometers. Soliton communications promises to reduce the dispersion limitation significantly. Solitons are specially shaped light pulses that take advantage of nonlinear properties of the fiber through an effect known as self-phase modulation (SPM). SPM counters the effects of dispersion so that the pulse width is maintained over extremely long distances. Neighboring pulse interactions, pulse shaping, and optimum repeater spacing are issues currently being studied. Recent efforts have demonstrated soliton communications using fiber amplifiers over trans-oceanic distances at 10 Gbps [9]. AT&T has joined with KDD of Japan in a venture to place a 9,000-km undersea link using solitons and fiber amplifiers between Seattle and Tokyo by 1996. The system is projected to carry 700,000 voice channels at a rate of 5 Gbps [10].

While several years are necessary before any of these new technologies are fully transitioned from the laboratories to the field, it is interesting to witness their development. Less than two years have past since the first fiber amplifier milestones were reported and already four companies offer turn-key fiber amplifiers. However, with price tags of \$15,000 - \$40,000 they are still mostly suitable for research applications.

ROV Telemetry

For years remotely operated vehicles, ROVs, have aided in undersea tasks including offshore platform inspection and repair, weapon recovery, cable replacement, and rescue. They are also helpful in scientifically characterizing ocean parameters using sensitive equipment to measure salinity, current, temperature, pressure, and depth. The ROVs are tethered to the support vessel with an umbilical cable which carries power and control signals down to the vehicle and retrieves vehicle data. This data takes the form of video images, high-resolution acoustic images, vehicle status, and computer commands. Fiber optics advances the capabilities of the ROV through its outstanding features of low loss, high bandwidth, and small size. The low loss allows the vehicle to have a greatly extended mission stand-off range. In the area of mine neutralization and under-ice exploration this is essential. The high bandwidth feature allows the vehicle to support sophisticated data collection equipment such as multiple cameras, stereoscopic cameras, and high-resolution sonar. It also allows much of the computer software needed for autonomous maneuvers to be handled and housed in a computer on board the support vessel. This reduces vehicle weight, power consumption, and cost. The small size allows a spool of fiber cable to be housed and deployed from the vehicle. For self-powered ROVs, operating solely on batteries, the fiber cable can be quite small and expendable, thereby maximizing packing density.

The NOSC Connection

The Ocean Engineering Division at NOSC, San Diego has pioneered ROV technology. It continues to be on the leading edge of advanced vehicle development. In the field of fiber optics for ROV telemetry it has also excelled [11]. Over the past ten years it has advanced the state of the art in several significant areas.

Early in the 1980's NOSC demonstrated the first fiber-optically guided torpedo [12]. The successful demonstration was the culmination of several years of research and development effort in producing a high-speed underwater fiber optic link that could remotely guide a torpedo. The advantages were clear: faster target acquisition rates, lighter torpedo weight, and transfer of the torpedo computer hardware to the support vessel. To achieve this, many fiber-optic components unique to undersea vehicles and not available at the time had to be developed.

Figure 2 depicts a simple block diagram of a typical fiber optic data link for a ROV. The link is divided into four major sections: the topside optics residing on the support vessel, the ROV optics residing inside the one-atmosphere electronics bottle of the vehicle, the optical pressure penetrator, and the fiber optic cable. As is seen, one feature distinguishing this system from a point-to-point system is that the link is bi-directional. The downlink transmits command and control data from the support vessel to the ROV. These commands can originate from an operator or a computer. The uplink sends ROV sensor data back to the support vessel to be processed and stored. Together the two links form a closed control loop for vehicle manipulation.

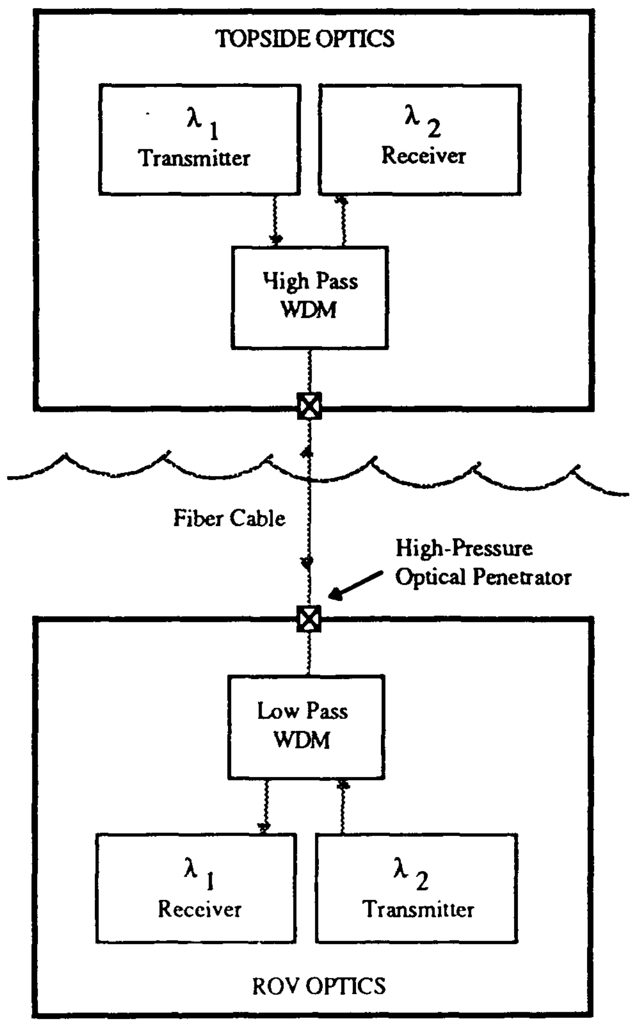

Figure 2. Block Diagram of ROV Fiber Optic Duplex Telemetry System

Bidirectional communication is performed over a single fiber element, making the system full duplex. The duplexing is achieved optically by using two separate wavelengths of light. These wavelengths are labeled λ_1 and λ_2 in the figure. The concept is referred to as wavelength division multiplexing and is similar to frequency division multiplexing of two different electronic frequencies.

At the heart of the duplexing scheme are two wavelength division multiplexers or WDMs. The WDM serves three functions: to inject outgoing light from the local transmitter into the fiber transmission cable, to extract incoming light from the distant transmitter and direct it to the local receiver, and to isolate the light signals between the local transmitter and receiver. The injection and extraction functions must be done efficiently with a minimal optical loss and the isolation must be high enough to prevent unwanted crosstalk between the two channels. These functions are achieved using optical fiber pigtails, graded-index (GRIN) lenses, and dichroic interference filters. Figure 3 illustrates the type of WDM built at NOSC. This approach is now a widely accepted method for producing WDMs with large channel isolations. The WDM is fabricated by sandwiching the dichroic filter between two GRIN lenses. The filter has a transmission characteristic that passes one wavelength and reflects the other. As is shown, light at λ_1 from the local transmitter is coupled via a fiber into the first lens. It reflects off of the filter and is directed into the transmission line fiber. Light coming from the distant transmitter at λ_2 enters the first lens, passes through the filter, passes through the second lens, and is directed via a fiber to the local receiver. The lenses provide the efficient coupling, less than 1-dB loss, and the filter provides the isolation, greater than 60 dB, between λ_1 and λ_2. For a complete duplex system, two complimentary WDMs are needed, one with a low-pass filter and one with a high-pass filter.

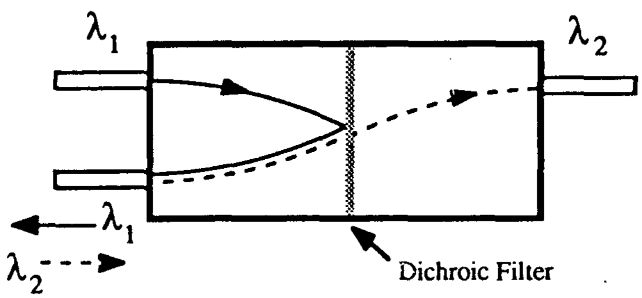

Figure 3. Optical Design for a Full-Duplex Wavelength Division Multiplexer

The low data rates and relatively short distance of the first demonstration link obviated the need for single-mode fiber and laser transmitters. The system used a multimode fiber cable, LED transmitters, and PIN photodiode receivers. NOSC built their own WDMs to operate at 0.83 and 1.06 µm, the wavelengths of light most commonly available from LED manufacturers at the time.

Another development necessary for a successful fiber optic ROV telemetry link is an optical, high-pressure bulkhead penetrator. This device efficiently transfers light from the cable into the electronics bottle and seals the bottle against the high ambient ocean pressure. GRIN lens techniques are used to collimate light across the pressure barrier. NOSC has been a world leader in developing these optical penetrators and holds several U. S. patents for their designs.

Critical to the success of the ROV telemetry link is the survival of the fiber cable in the harsh ocean environment. The cable must withstand crushing ambient pressures and near freezing temperatures. In addition, for fiber-guided torpedoes, it must tolerate high cable payout speeds. NOSC has been the leader in developing undersea fiber cable designs for fiber optic ROV telemetry. For expendable tethers, such as those used for torpedoes, the cable carries no electrical power. The objective is to build the smallest diameter cable that can survive. The design is an epoxy / fiber-glass reinforced matrix surrounding the buffered fiber. The microcable is slightly larger than the buffered fiber but capable of survival, both physically and optically, at high pressures and low temperatures.

Extremely high packing density in a free-standing spool is achieved with the small cable. This allows long cable lengths to be stowed compactly. The spool is placed inside the vehicle and the cable is deployed in a center pull-out technique along the spool's longitudinal axis as the vehicle moves through the water. A winding machine has been developed at NOSC to facilitate the spooling of the microcable. The cable coils are precision wound in a close-packed geometry and held in place by application of a low-bond-strength adhesive. As the cable is wound onto the spool a 360-degree pretwist is applied that opposes the twist that occurs during payout. This results in a torsion-free cable during deployment, eliminating the tendency for the cable to hackle should it go slack in the water column.

Most ROVs require a reusable tether cable containing electrical wires for power transport as well as optical fibers. The power is used for propulsion, lights for the cameras, sensors, and electronics. These hybrid cables are considerably larger than the expendable microcables. In most instances the cable is stored and deployed off of the support vessel. A cable winch, equipped with optical slip rings, dispenses the cable as the ROV swims about below. Extended mission lifetime is available for ROVs with externally supplied power. Larger propulsion systems are sometimes needed to move the ROV through the water due to the drag of the larger cable, however this cable, for most applications is much smaller than its coaxial counterpart.

Many fiber optic telemetry systems for ROVs are simple compared to the long-haul undersea links. The mission stand-off range and total sensor bandwidth requirements are low enough that inexpensive components can be utilized. Short-wavelength LED transmitters coupled to multimode fibers and PIN photodiode receivers are adequate. For use as a simple design aid, figure 4 provides information on stand-off range as a function of data rate for full-duplex, fiber optic ROV telemetry links.

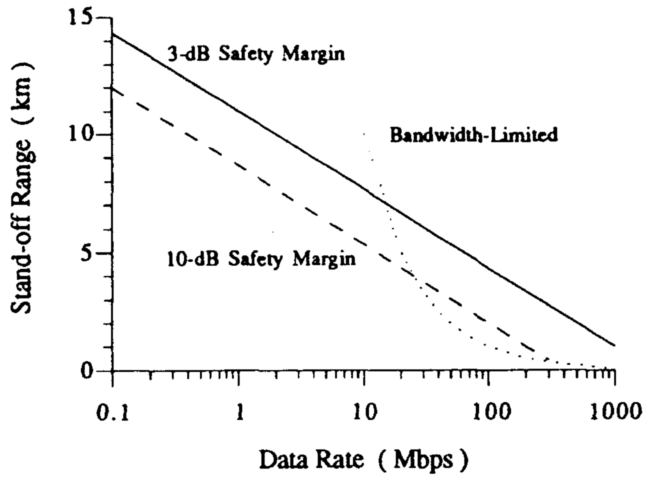

Figure 4. Stand-Off Range vs. Data Rate for LED / Multimode Fiber / PIN Receiver Systems

While the plot in figure 4 extends to 1000 Mbps, LED-based systems are only good to about 250 Mbps. This is considered the top end of performance for LEDs. The dotted curve labeled "Bandwidth-Limited" represents the maximum stand-off length attainable and must be used for data rates above 10 Mbps. Comparing figure 4 with figure 1, note the vast differences in range attainable between an LED / multimode fiber based system and a laser / single-mode fiber based system. At a data rate of 10 Mbps and using a 10-dB safety margin, the laser system yields 160 km compared to only about 5 km for the LED system. Of course, the decision of which component set to use is based on application, reliability, and cost.

NOSC has combined the duplex concept used for ROVs with the long-distance optical components employed by the telecommunications companies to demonstrate a long-distance, unrepeatered bidirectional link [13]. Using duplex wavelengths of 1.3 and 1.55 μm, transmission over more than 185 km has been demonstrated to date and efforts are being applied to extending that distance further, through the use of an optical preamplifier and wavelengths of 1.53 and 1.56 μm [14].

FIBER OPTIC SENSORS

The field of fiber optic sensors is exploding. Many designs are finding their way to undersea applications. An optical fiber is used as the sensing element and is also used to carry light to and from one or more sensors for remote sensing applications. Fiber used in telecommunications must be immune to external physical disturbances such as pressure and temperature that influence the propagation characteristics of the fiber. Microbending can cause severe losses in these fibers if not minimized or completely eliminated. The cable design protects the fiber against these changes. A fiber sensor applies the opposite approach and takes advantage of the high sensitivity a fiber has to external forces. A fiber sensor principally operates by the alteration of one or more of the characteristics of the light traveling through it. The amplitude or intensity, the polarization, the wavelength, or the relative phase of the light is changed in proportion to a physical perturbation applied to the sensor. In effect, the light is modulated by the physical field. To retrieve the information, a receiver must decode the modulated light signal.

Incoherent Sensors

Sensors are divided into two categories: incoherent and coherent sensors. Incoherent sensors represent the simplest, most inexpensive type. Figure 5 illustrates the fundamentals of an incoherent sensor. It consists of a light source, a transmission and sensor fiber, and a detector / receiver. Light from an incoherent, relatively broadband source is used. This can be a white-light source or a narrower band LED. In a simple implementation the sensor is part of a long fiber link. The light is carried from the source through the sensor and on to a detector. When an external, physical perturbation is applied to the sensor, the intensity of the light is diminished proportionately. In other designs, the light polarization is rotated due to the measurand and this in turn is converted, via a polarized filter, into an intensity change at the receiver.

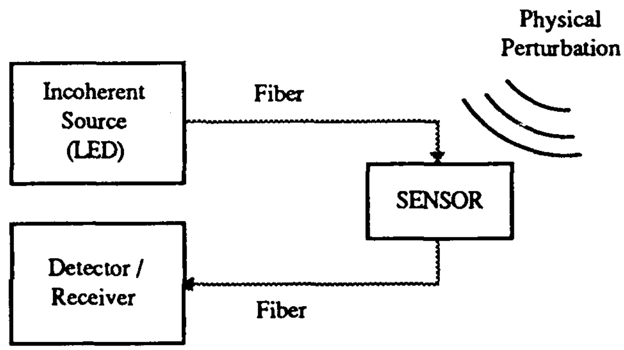

Figure 5. Incoherent Fiber Optic Sensor Diagram

Several schemes have been developed [15]. One is used to measure displacement [16]. The sensor is simply a moveable gap between two fiber endfaces. The gap bridges the entire link together. As displacement is applied, such as might be caused from an acoustic wave, the gap widens causing an increase in the coupling loss across the gap. This loss is translated to the detector in the form of a lower intensity. Lateral force can be measured with a fiber sensor. Microbend-induced attenuation is employed as the transduction mechanism. The sensor is comprised of a fiber sandwiched between two sets of opposing teeth. A lateral force is applied to one side, pushing the teeth together and slightly deforming the fiber. The deformation causes light traveling in the fiber to escape and this change in transmission is detected. A variation of this approach was used to measure deflection on an offshore oil platform [17]. An array of sensors was attached to the sides of the tension legs supporting the platform. The sensor data were time division multiplexed to a receiver which separated the information and decoded it. The multiplexing was achieved within the fiber network. The fibers were set in a parallel arrangement and the relative distances between each sensor automatically separated the return signals in time.

Temperature can be measured with a fiber optic sensor. A coating with a low thermal-expansion coefficient compared to glass is applied around a bare fiber. As the temperature varies the coating elongates and contracts. These forces cause microbending loss in the fiber and an associated light level change. A similar effect can be used to measure hydrostatic pressures. The pressure-induced stresses generate detectable microbending losses.

The Ocean Engineering Division at NOSC is involved in fiber optic sensors and has developed and patented a fiber-optic strain gauge [18]. Recall that optical fiber experiences stress corrosion in the presence of moisture and stress, ultimately causing premature fiber failure. It was necessary to design a device that could measure the residual strain inside an optical cable deployed in service underwater. The strain gauge uses an all-optical loop formed by the cable being measured. A resonant frequency is developed, which changes as the cable is strained. A strain resolution of 0.1% was achieved. Current work proposes to increase the finesse of the resonator by adding a small piece of erbium-doped fiber to the loop in an attempt to offset passive loop losses.

In a joint effort between NOSC and the U. S. Naval Postgraduate School, Monterey, an incoherent fiber optic angle encoder has been developed and patented [19]. The device can be used as a compass or to measure angular orientation of sonobuoys, hydrophones, and ROVs. Light is transmitted through an encoded disk impressing angular information onto the intensity or polarization of the light beam as the disk rotates. Angular resolution of 2 degrees was measured. Device miniaturization promises improved resolutions down to 0.5 degrees.

Coherent Sensors

While relatively simple to implement, incoherent sensors have limitations. They rely on stable source output powers. Resolution and repeatability is limited by random variations of the source. In contrast, coherent sensor techniques harness the ability to detect small changes in phase of a highly coherent lightwave. and are insensitive to power fluctuations. Figure 6 illustrates a simple coherent fiber optic sensor configuration.

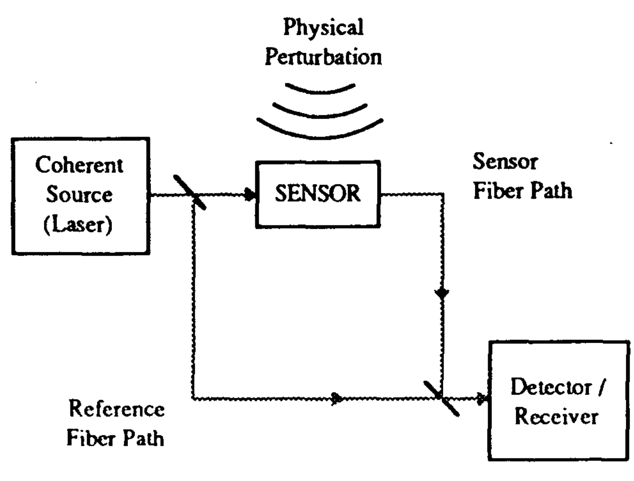

Figure 6. Coherent Fiber Optic Sensor Diagram

The sensor system is based on the optical interference between two coherent light beams. One beam passes through the sensor path of the system and the other passes through the reference path. As the phase in the sensor path changes due to some external perturbation, the resultant interference at the detector changes. When the two beams are in phase, the detector registers a maximum intensity and when the two are 180 degrees out of phase the two subtract to give a minimum intensity at the detector. Thus minute variations in phase shifts can be measured. Phase shifts in the sensor path can occur due to different effects. If the length of the sensor path changes, this results in a phase shift. The phase shift is proportional to the length change. Because the wavelength of light used in the sensor system is around 1 μm, the strain in a fiber can be measured very precisely. Displacements as small as 10^{-10} m have been measured. Strain-induced phase shifting forms the basis for many coherent sensor systems. Refractive index changes are also harnessed to produce phase shifts.

For undersea applications, coherent sensors are being developed for all-optical hydrophones [20]. One approach is to wrap the sensor fiber around a compliant mandrel. An incident acoustic wave deforms the mandrel and subsequently the fiber undergoes strain. This strain is converted into a detectable phase shift. Encouraging results have been reported in the low frequency band. At a frequency of 1 kHz, a minimum pressure response of 30 dB RE 1μPa has been measured. The response is very flat from 10 Hz -10 kHz. For comparison, an H56 piezoelectric hydrophone gives about 28 dB RE 1μPa at 1 kHz, but its performance is worse than the optical hydrophone at lower frequencies. The expected theoretical performance of the optical hydrophone is 0 dB RE 1μPa [14].

The Navy is investing heavily in fiber optic sensor research. All-optical sensors offer more than just potential improvements in sensitivity. The low loss and high bandwidth of the fiber allows the fiber sensors to be deployed to remote locations and applied to high speed sensing. The signal remains optical and obviates the need for transmitting electrical current. The geometric versatility allows multiple-fiber sensor networks at a reduced size. The fibers are safe to deploy in combustible areas because they do not cause sparks. The fibers are not susceptible to EMI and therefore can be used around high magnetic fields.

The level of interest in fiber optic sensors grows as the number of designs dramatically increases. Within the Navy, most of the fiber optic sensor research is being conducted at NOSC, the NPG School, NRL, and NUSC. Outside agencies include AT&T, Honeywell, JPL, Litton, Martin-Marrietta, and the NASA/Lewis Research Center.

REFERENCES

[1] P. K. Runge and P. R. Trischitta, " The SL Undersea Lightwave System", IEEE Journal on Selected Areas in Communications, Vol. SAC-2, No. 6, pp. 784-793, November 1984.

[2] P. A. Dawson and K. D. Fitchew, "Repeater Design Requirements", British Telecommunications Engineering, Vol. 5, pp. 97-103, July 1986.

[3] S. Shibata, M. Horiguchi, S. Mitachi, and T. Manabe, "Prediction of loss minima in infrared optical fibers", Electron. Lett., pp. 775-777, 1981.

[4] B. Bendow, "Mid-IR fiber optics technology: A study and assessment," NOSC Final Report CR 243, February 1984.

[5] T. Okoshi, "Recent advances in coherent optical fiber communication systems", J. Lightwave Tech., Vol. LT-5, pp. 44-52, 1987.

[6] Grasso, G., Cheung, N.K. , et. al.,"An 11 Gbit/sec 260 km transmission experiment using a directly modulated DFB laser with two ER-doped amplifiers and clock recovery", Proc. of ECOC (Gothenburg), Postdeadline Session Paper PDA 10, 1989.

[7] K. Aida, H. Masuda, and A. Takada, "Long-span IM/DD Transmission System Experiment using High-Efficiency EDF Amplifiers", Proceedings of Optical Amplifiers Topical Meeting, Paper TuC5, pp.164-167, 6-8 August 1990.

[8] Y. K. Park, J-M P. Delavaux, R. E. Tench, and T. W. Cline, "1.7 Gb/s-419 km Transmission Experiment using a Shelf-Mounted FSK Coherent System and Packaged Fiber Amplifier Modules", Proceedings of Optical Amplifiers Topical Meeting, Paper TuC4, pp.160-163, 6-8 August 1990.

[9] K. J. Blow and N. J. Doran, "Long-distance amplified soliton systems: a novel modulation concept", IEEE Proceedings on the Optical Fiber Conference '91, Paper ThL3, 18-22 February 1991.

[10] J. J. Keller, "New AT&T System May Sharply Boost Capacity of Marine Transmission Cables", Wall Street Journal, p. B4, 2 July 1990.

[11] M. E. Kono and M. R. Brininstool, "Towards a Universal Design for ROV Telemetry via Fiber Optics", Proc. of International Telemetering Conference, Vol.14, pp. 523-535, 1983.

[12] M. Kono, M. Brininstool, and S. Cowen, "Fiber Optic Telemetry for the REGAL Torpedo", NOSC Technical Report TR 920, April 1984.

[13] M. R. Brininstool, "104-km Unrepeatered Bidirectional Fiber Optic Demonstration Link", NOSC Technical Report TR 1185, May 1987.

[14] M.R. Brininstool, S.J. Cowen, W.H. Marn, and M.C. Scallon, "Long-Distance Repeaterless Duplex Fiber-Optic Demonstration System", NOSC Technical Report TR 1411, February 1991.

[15] R. P. De Paula and E. L. Moore, "Fiber Optic Sensor Overview", Proc. of SPIE, Vol. 566, Fiber Optic and Laser Sensors III, [566-01], 1985.

[16] N. Lagakos, "Multimode optical fiber displacement sensor", Applied Optics, Vol. 20, p. 167, 1981.

[17] S. A. Kingsley, "Distributed Fiber Optic Sensors: An Overview", Proc. of SPIE, Vol. 566, Fiber Optic and Laser Sensors III, [566-68], 1985.

[18] M. R. Brininstool, "Measuring longitudinal strain in optical fibers", Optical Engineering, Vol. 26, No. 11, pp. 1112-1119, November 1987.

[19] J. T. Newmaster, M. R. Brininstool, T. Hofler, S. L. Garrett, "Remote fiber optic sensors for angular orientation", Proc. of SPIE, Vol. 838, Fiber Optic and Laser Sensors V, pp. 28-38, August 1987.

[20] J. A. Bucaro, E. F. Carome, and H. D. Dardy, "Fiber optic hydrophone", J. of Acoustic. Soc. Am., Vol.62, No. S1, pp. 1302-1304, 1977

OCEANIC APPLICATIONS OF FIBER OPTICS

Michael R. Brininstool

Naval Ocean Systems Center
Ocean Engineering Division
San Diego, CA 92152

ABSTRACT

Oceanic applications of fiber optics are rapidly advancing, following on the heels of the more mature land-based telecommunications systems. While many features of each arena are similar, undersea fiber systems demand unique capabilities. Components capable of withstanding brutal hydrostatic pressures and near freezing temperatures had to be developed. This paper highlights undersea fiber optic systems and their features. It focuses on long distance telecommunications and remotely-operated-vehicle (ROV) links. Also addressed is the emerging technology of fiber optic sensors. These designs use the fiber as a sensing element to detect such variables as displacement, pressure, temperature, strain, and rotation.

INTRODUCTION

Fiber optics is increasingly becoming the media of choice in a wide assortment of undersea applications. The main thrust of development efforts are directed toward fiber optic telemetry and sensors. Several distinct advantages over conventional wire technology are exploited. Fibers possess very low intrinsic attenuation of the optical power traveling down the waveguide. With the common silica-glass based fiber used today, attenuations as low as 0.2 dB/km are achievable. This compares dramatically to coaxial transmission lines where the attenuation varies as a function of carrier frequency and can range from 4 to 100 dB/km for moderate bandwidths of 100 MHz.

Optical fibers have extremely large bandwidth-length products. The single-mode fibers, at the high performance end of the fiber product line, have bandwidth-length products as high as 800 GHz-km. Even the more modest multimode fibers can provide 1 GHz-km. These values translate into huge bandwidth-limited transmission distances. However, for most applications, it is the fiber attenuation, not the bandwidth that usually limits the ultimate distance a signal can be transmitted. For trans-oceanic communications links, the attenuation-limited distance determines how many repeaters are required and thus directly influences the system cost. The latest fiber optic transatlantic link was brought on-line in November 1989. Known as TAT-8, the 6100-km system bridges the east coast of the United States to Great Britain and France with a telephone system capable of simultaneously transmitting 40,000 digitized voice channels at a data rate of 280 Mbps [1]. The system requires only 125 repeaters, spaced 50 km apart. Future systems will be able to extend that spacing to 100-150 km. TAT-7 was the last transatlantic coaxial cable system placed in service. In comparison, the repeater spacing was only about 10 km and the cable carried 4200 analog phone circuits.

Fiber optics will continue to play a large role in undersea links, increasing channel capacity and repeater spacing distance. Both of these improvements provide great cost savings. As the number of voice channels grows the cost per channel diminishes. The TAT-8 system cost $360 million, or $9,000 for each of its 40,000 voice lines. Capacity expansion by at least a factor of 20 is anticipated over the next five years. Each repeater cost about $800,000 for TAT-8. New optical amplifier technology aims at reducing both the number, complexity, and cost of a repeater while improving the reliability.

Small size and light weight are two other outstanding features optical fiber offers to undersea links. As an example an expendable, underwater tether cable for ROV telemetry has a diameter of only 900 µm and weighs less than 1 kg/km in air and is nearly neutrally buoyant in water. A coaxial cable with comparable bandwidth is about 30 mm in diameter and weighs over 1110 kg/km. For ROVs, the size and weight savings means reduced cable drag, extended mission lifetime, and enhanced packing density of the spooled cable housed within the vehicle.

TELEMETRY APPLICATIONS

This section addresses a few applications of fiber optics applied to undersea telemetry. Included are long-haul systems and ROV communication links.

Long-Haul Systems

Most of the fiber deployed for long-haul trans-oceanic systems is used for carrying telephone channels. Shared on the telephone lines are facsimile and computer data and, to a growing extent, video transmission. AT&T is playing a significant role in installing trans-oceanic links. In addition to the TAT-8 system, another trans-Atlantic route, TAT-9, is expected to be completed in December 1991. Taking advantage of newer 1.55-µm laser technology, it will carry 80,000 voice channels over three 560-Mbps fiber pairs, with 100-km repeater spacings. Another route, TRANSPAC-3, or TPC-3, will run from Hawaii to Japan via Guam. All current designs use similar approaches. To achieve long repeater spacings the fiber link consists of long-wavelength high-powered laser-diode transmitters, low-loss single-mode optical fibers, and high-sensitivity PIN-FET receivers.

In addition to power budget considerations, it is also important that the fiber system maintain adequate bandwidth over the repeater span. Laser diodes have very high modulation bandwidths, with some capable of 10 GHz. The coherence of the laser aids in maximizing the fiber bandwidth. Its narrow spectral linewidth minimizes pulse spreading due

to chromatic dispersion in the fiber. The single-mode fiber bandwidth is virtually unlimited when used with optimized laser sources. Receiver bandwidth is kept close to the system bandwidth to reject out of band electronic noise. This optimizes the signal-to-noise ratio and the sensitivity.

Because the noise bandwidth influences receiver sensitivity, repeater spacings are dependent on the required data rate of the system. As the system data rate increases the span length decreases since more incident optical power is required at the receiver to overcome the noise. This is illustrated in Figure 1, plotting repeater spacing as a function of data rate for a fiber link comprised of a laser transmitter, a single-mode fiber, and a PIN-FET receiver. The two curves represent results from using two different values for optical safety margin. The safety margin insures against future link degradations due to laser output power reduction, increased fiber attenuation, and potential repairs. The margin is added to the total optical loss allocated for fiber attenuation, splice and connector loss, and other passive component losses incurred along the path. A 3-dB safety margin is considered minimal, especially for undersea applications and 10-dB margin is more practical. The TAT-8 system employs a 9-dB margin: 2 dB allowance for repair, 4 dB for laser ageing, and 3 dB for an end of life margin [2].

Figure 1 is used to quickly determine the maximum data rate capacity a fiber link can manage if the span distance is given. For example, supposed a repeaterless link is to be installed over 160 km, approximately 100 miles. For a 10-dB safety margin, the data rate limit is about 10 Mbps. This is equivalent to roughly 150 uncompressed voice channels. The figure can also be used conversely to determine repeater spacing for a link given the system data rate.

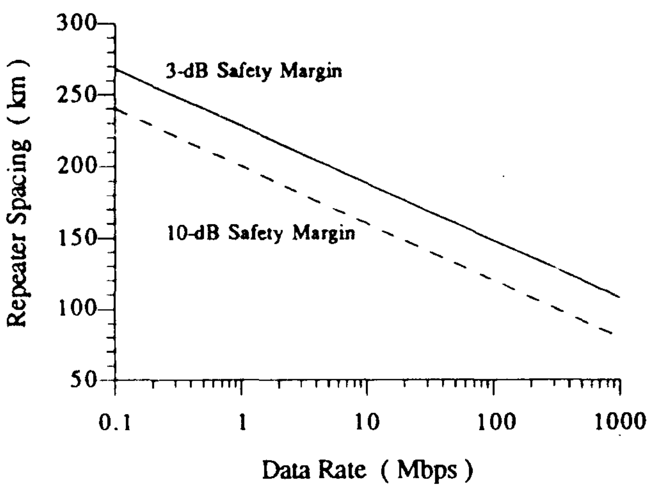

Figure 1. Repeater Spacing for Laser / Single-mode Fiber / PIN-FET Receiver Systems

The repeater for an undersea link houses the receiver, transmitter, power circuitry, and associated supervisory control electronics. The control electronics monitors the health of the repeater components and notifies a master supervisor of any trouble. For higher reliability, redundancy is used. The TAT-8 system uses six optical fibers in its cable. Two pairs are active and one pair is on standby. The repeater has three extra lasers that can be switched remotely by the master supervisor in the event of a laser and / or fiber failure. The repeater electronics are maintained at one atmosphere pressure. The housing seals around the ends of the cable terminations.

Submarine Cable

The underwater fiber optic cable must meet several stringent requirements to maintain the integrity of the fiber. The cable must protect the fiber from longitudinal stresses, moisture intrusion, large hydrostatic pressure exposure, and extreme thermal excursions.

The fiber element is fundamentally very strong. However, microscopic defects along the surface of the fiber weaken the element considerably. Adding to this problem is moisture. In the presence of stress and moisture, the flaws in the fiber surface grow, further weakening the fiber due to stress corrosion. If allowed to continue, the flaw will ultimately sever the fiber. Although the fiber used for undersea cables is typically much stronger than that used in terrestrial cable, it still must be protected. The fibers are normally embedded in a stiff, matrix material, such as Hytrel™, which forms a bonded unit. Units housing multiple fibers place the fibers in a helix around a central steel "king" wire. Any axial load applied to the unit is taken up first by the king wire. Kevlar™ is another strength member used commonly in cables. Additional strengthening is added depending on the expected loads the cable will undergo during installation and service.

The TAT-8 system uses two types of cables: one for deep water and one for shallow water service. The deep water cable has a layer of galvanized steel wires enclosing the fiber optic unit in a pressure tolerant "cage". A thin copper layer is welded around the steel layer. The copper is used to carry the electrical current necessary to power the repeaters. The combination of the copper and steel layer provides a water-tight pressure-tolerant chamber for the fibers. Since the cable is manufactured on the surface, the fibers remain at one atmosphere for the entire system lifetime. This pressure-tolerant chamber is vital to the survival of the fiber elements. It eliminates the water intrusion, thereby reducing stress corrosion problems. The steel wires also significantly increase the tensile strength of the cable.

The optical transmission integrity of the fibers is also well preserved. If exposed to high levels of hydrostatic pressure, the fiber unit will begin to buckle. This buckling attributes to microbending attenuation in the fibers. If severe, the fibers can go completely dark. The steel strength members prevent hydrostatic pressure from effecting the fiber unit. Under pressure the steel wires lock up, forming a rugged barrier. The copper layer serves as a water and hydrogen barrier. Hydrogen, from filling compounds in the cable, has been shown to diffuse into the fiber increasing optical transmission losses due to absorption.

Thermal-induced contractions in the fiber unit at low temperatures can also cause microbend attenuation. This contraction is restricted by the helix within the Hytrel™ matrix and by the steel strength members. Surrounding the

strength members is a thick layer of low density polyethylene. This layer serves as the insulation for the electrical current. A sea-water ground return is used and the current must be isolated.

The shallow water cable has thick galvanized steel armor wires surrounding the deep water cable structure. This armoring protects the cable against accidental fishing trawler damage and abrasion caused by continual movement across coral and rocks.

The Future of Long Haul

There are several exciting technologies emerging that promise great improvements for long-haul undersea links. They are aimed at extending the repeater spacing and channel data rate capacity. Four significant technologies discussed here are mid-infrared fiber optics, coherent fiber optics, optical fiber amplifiers, and soliton communications.

The TAT-8 system uses fiber made from silica glass and transmits data over the fiber with laser diodes emitting in the 1.3-μm wavelength range. This wavelength was chosen because it corresponds to a low-attenuation, low-dispersion window in silica glass. Also the 1.3-μm laser technology was the most mature at the time of development. Since then the 1.55-μm wavelength has become the color of choice. The glass exhibits a lower attenuation at 1.55 μm than at 1.3 μm and thus data can be sent further. To maintain the high bandwidth requirement, fiber with the minimum dispersion wavelength shifted to 1.55 μm is used. Figure 1 was generated based on a 1.55-μm laser transmitter. This represents the wavelength for the lowest attenuation, 0.2 dB/km, attainable using silica-based glass. New types of fiber made from heavy-metal fluoride glass are being developed. When used at wavelengths of 2.7 μm, these fibers have the potential for attenuations as low as 0.001 dB/km [3]. Researchers at the Naval Research Lab, AT&T, and Corning have independently achieved losses of 1 dB/km, down from 20 dB/km just four years ago [4]. The rapid improvements are attributable to applying the lessons learned in making low-loss silica fiber over the last twenty years. Many obstacles must still be overcome. Suitable sources and detectors must be developed to operate in the mid-infrared region. Detectors must be cryogenically cooled to achieve high sensitivities due to thermal-generated noise currents in the detector at these wavelengths. The fiber material has low strength and a low melting temperature compared to silica. Fluoride glass has a very low melting temperature, 300 °C, compared to over 1000 °C for silica. The fluoride tends to be hygroscopic and readily absorbs water.

Presently, all undersea long-haul fiber systems use intensity modulation (IM) of the lasers to transmit digital data. Direct detection (DD) of the signals converts the intensity into electrical current. Coherent fiber optic communication systems (COFOCS) utilize the coherent nature of spectrally pure, single-longitudinal mode lasers. Information is impressed on the phase of the lightwave instead of the intensity, as is done with direct-detection systems. At the receiver, optical heterodyne mixing of the signal with a local optical oscillator provides improved sensitivities close to the quantum limit. Improvements in sensitivity of 5 - 20 dB can be achieved over direct detection schemes [5]. This translates into detecting weaker signals and being able to extend the repeater spacing distance. Receiver channel selectivity is another benefit COFOCS provides. More channels can be packed together on a single fiber line by separating them at slightly different optical frequencies, thereby increasing the ultimate bandwidth capacity of the fiber. Many technical issues are being addressed with COFOCS. The heterodyne receiver is very sensitive to the polarization state of both the local oscillator and the signal fields. Random phase fluctuations of the transmitter also cause degraded reception.

Probably the most publicized technical advance for extending repeater distance is in the area of optical fiber amplifiers. Fiber amplifiers are inserted directly into the optical path and provide gain to the signal. A coil of fiber, typically 10-100 meters long, is lightly doped with trivalent rare-earth ions such as erbium. The fiber coil is then excited with a laser-diode pump source using a WDM to couple the pump power into the coil. The pump power raises the rare-earth ions in the fiber coil to an excited metastable state of population inversion. Under this condition, according to quantum electronics, a signal passing through the coil with a wavelength equivalent to the transition between excited and ground states experiences a net gain due to stimulated emission. The principles are similar to gain developed in optically pumped lasers. Fiber amplifiers have many outstanding features. The fiber geometry offers unique advantages. The fiber is easily interfaced to the transmission line fiber. Fusion splices give low-loss, low-reflection coupling. The pump and signal powers are confined to a very small core area over an extended interaction length. This provides for efficient pump absorption over long lengths. The fiber gain is polarization insensitive. Fiber amplifiers are potentially more reliable and smaller than their opto-electronic counterparts. Unlike opto-electronic repeaters, the fiber amplifiers are essentially bit rate transparent. Experiments have shown a limit in the Tbps range [6]. Limitations in long-distance systems with multi-repeater fiber amplifiers include optical noise build-up as the light passes through the amplifier cascade chain and fiber dispersion which limits the data rate capacity.

The future will see rapid advances in gain performance and packaging of fiber amplifiers as they become widely adopted for an assortment of long-distance, multi-access distribution network, and sensor applications. One recent report stated fiber amplifier repeater gains of 55 dB were achieved. The fiber amplifier was employed in a laboratory IM/DD system and a 1.8-Gbps nonrepeatered transmission over a length of 308 km was accomplished [7]. Long-distance links employing both coherent detection and fiber amplifiers have been reported. One experiment at AT&T achieved 1.7-Gbps transmission over 419 km using an FSK coherent system with fiber amplifiers [8].

Communications experiments utilizing the physics of optical solitons are being conducted. As fiber amplifiers help to extend the power-limited distances for undersea links, the systems become bandwidth or dispersion-limited. The

narrow optical pulses spread into each other and become indistinguishable after many hundreds of kilometers. Soliton communications promises to reduce the dispersion limitation significantly. Solitons are specially shaped light pulses that take advantage of nonlinear properties of the fiber through an effect known as self-phase modulation (SPM). SPM counters the effects of dispersion so that the pulse width is maintained over extremely long distances. Neighboring pulse interactions, pulse shaping, and optimum repeater spacing are issues currently being studied. Recent efforts have demonstrated soliton communications using fiber amplifiers over trans-oceanic distances at 10 Gbps [9]. AT&T has joined with KDD of Japan in a venture to place a 9,000-km undersea link using solitons and fiber amplifiers between Seattle and Tokyo by 1996. The system is projected to carry 700,000 voice channels at a rate of 5 Gbps [10].

While several years are necessary before any of these new technologies are fully transitioned from the laboratories to the field, it is interesting to witness their development. Less than two years have past since the first fiber amplifier milestones were reported and already four companies offer turn-key fiber amplifiers. However, with price tags of $15,000 - $40,000 they are still mostly suitable for research applications.

ROV Telemetry

For years remotely operated vehicles, ROVs, have aided in undersea tasks including offshore platform inspection and repair, weapon recovery, cable replacement, and rescue. They are also helpful in scientifically characterizing ocean parameters using sensitive equipment to measure salinity, current, temperature, pressure, and depth. The ROVs are tethered to the support vessel with an umbilical cable which carries power and control signals down to the vehicle and retrieves vehicle data. This data takes the form of video images, high-resolution acoustic images, vehicle status, and computer commands. Fiber optics advances the capabilities of the ROV through its outstanding features of low loss, high bandwidth, and small size. The low loss allows the vehicle to have a greatly extended mission stand-off range. In the area of mine neutralization and under-ice exploration this is essential. The high bandwidth feature allows the vehicle to support sophisticated data collection equipment such as multiple cameras, stereoscopic cameras, and high-resolution sonar. It also allows much of the computer software needed for autonomous maneuvers to be handled and housed in a computer on board the support vessel. This reduces vehicle weight, power consumption, and cost. The small size allows a spool of fiber cable to be housed and deployed from the vehicle. For self-powered ROVs, operating solely on batteries, the fiber cable can be quite small and expendable, thereby maximizing packing density.

The NOSC Connection

The Ocean Engineering Division at NOSC, San Diego has pioneered ROV technology. It continues to be on the leading edge of advanced vehicle development. In the field of fiber optics for ROV telemetry it has also excelled [11]. Over the past ten years it has advanced the state of the art in several significant areas.

Early in the 1980's NOSC demonstrated the first fiber-optically guided torpedo [12]. The successful demonstration was the culmination of several years of research and development effort in producing a high-speed underwater fiber optic link that could remotely guide a torpedo. The advantages were clear: faster target acquisition rates, lighter torpedo weight, and transfer of the torpedo computer hardware to the support vessel. To achieve this, many fiber-optic components unique to undersea vehicles and not available at the time had to be developed.

Figure 2 depicts a simple block diagram of a typical fiber optic data link for a ROV. The link is divided into four major sections: the topside optics residing on the support vessel, the ROV optics residing inside the one-atmosphere electronics bottle of the vehicle, the optical pressure penetrator, and the fiber optic cable. As is seen, one feature distinguishing this system from a point-to-point system is that the link is bi-directional. The downlink transmits command and control data from the support vessel to the ROV. These commands can originate from an operator or a computer. The uplink sends ROV sensor data back to the support vessel to be processed and stored. Together the two links form a closed control loop for vehicle manipulation.

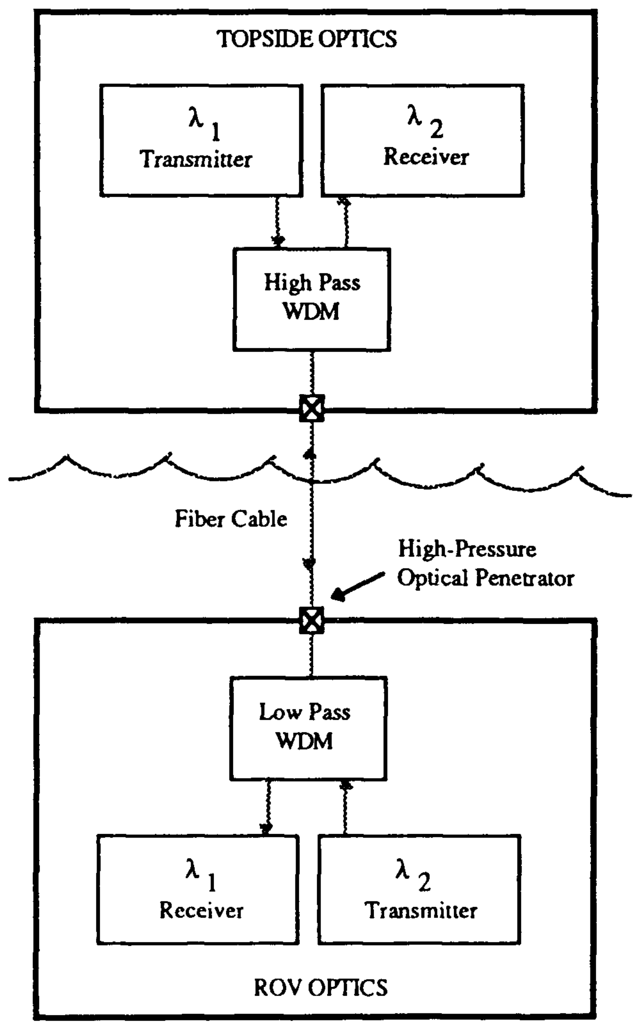

Figure 2. Block Diagram of ROV Fiber Optic Duplex Telemetry System

Bidirectional communication is performed over a single fiber element, making the system full duplex. The duplexing is achieved optically by using two separate wavelengths of light. These wavelengths are labeled λ_1 and λ_2 in the figure. The concept is referred to as wavelength division multiplexing and is similar to frequency division multipiexing of two different electronic frequencies.

At the heart of the duplexing scheme are two wavelength division multiplexers or WDMs. The WDM serves three functions: to inject outgoing light from the local transmitter into the fiber transmission cable, to extract incoming light from the distant transmitter and direct it to the local receiver, and to isolate the light signals between the local transmitter and receiver. The injection and extraction functions must be done efficiently with a minimal optical loss and the isolation must be high enough to prevent unwanted crosstalk between the two channels. These functions are achieved using optical fiber pigtails, graded-index (GRIN) lenses, and dichroic interference filters. Figure 3 illustrates the type of WDM built at NOSC. This approach is now a widely accepted method for producing WDMs with large channel isolations. The WDM is fabricated by sandwiching the dichroic filter between two GRIN lenses. The filter has a transmission characteristic that passes one wavelength and reflects the other. As is shown, light at λ_1 from the local transmitter is coupled via a fiber into the first lens. It reflects off of the filter and is directed into the transmission line fiber. Light coming from the distant transmitter at λ_2 enters the first lens, passes through the filter, passes through the second lens, and is directed via a fiber to the local receiver. The lenses provide the efficient coupling, less than 1-dB loss, and the filter provides the isolation, greater than 60 dB, between λ_1 and λ_2. For a complete duplex system, two complimentary WDMs are needed, one with a low-pass filter and one with a high-pass filter.

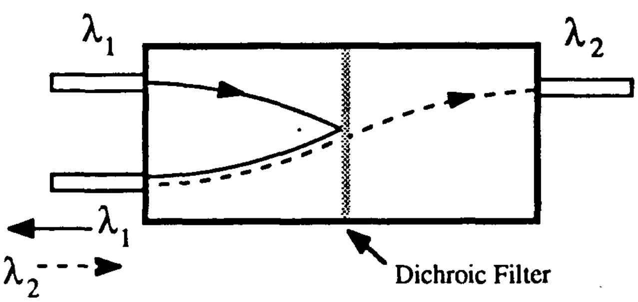

Figure 3. Optical Design for a Full-Duplex Wavelength Division Multiplexer

The low data rates and relatively short distance of the first demonstration link obviated the need for single-mode fiber and laser transmitters. The system used a multimode fiber cable, LED transmitters, and PIN photodiode receivers. NOSC built their own WDMs to operate at 0.83 and 1.06 µm, the wavelengths of light most commonly available from LED manufacturers at the time.

Another development necessary for a successful fiber optic ROV telemetry link is an optical, high-pressure bulkhead penetrator. This device efficiently transfers light from the cable into the electronics bottle and seals the bottle against the high ambient ocean pressure. GRIN lens techniques are used to collimate light across the pressure barrier. NOSC has been a world leader in developing these optical penetrators and holds several U. S. patents for their designs.

Critical to the success of the ROV telemetry link is the survival of the fiber cable in the harsh ocean environment. The cable must withstand crushing ambient pressures and near freezing temperatures. In addition, for fiber-guided torpedoes, it must tolerate high cable payout speeds. NOSC has been the leader in developing undersea fiber cable designs for fiber optic ROV telemetry. For expendable tethers, such as those used for torpedoes, the cable carries no electrical power. The objective is to build the smallest diameter cable that can survive. The design is an epoxy / fiber-glass reinforced matrix surrounding the buffered fiber. The microcable is slightly larger than the buffered fiber but capable of survival, both physically and optically, at high pressures and low temperatures.

Extremely high packing density in a free-standing spool is achieved with the small cable. This allow long cable lengths to be stowed compactly. The spool is placed inside the vehicle and the cable is deployed in a center pull-out technique along the spool's longitudinal axis as the vehicle moves through the water. A winding machine has been developed at NOSC to facilitate the spooling of the microcable. The cable coils are precision wound in a close-packed geometry and held in place by application of a low-bond-strength adhesive. As the cable is wound onto the spool a 360-degree pretwist is applied that opposes the twist that occurs during payout. This results in a torsion-free cable during deployment, eliminating the tendency for the cable to hackle should it go slack in the water column.

Most ROVs require a reusable tether cable containing electrical wires for power transport as well as optical fibers. The power is used for propulsion, lights for the cameras, sensors, and electronics. These hybrid cables are considerably larger than the expendable microcables. In most instances the cable is stored and deployed off of the support vessel. A cable winch, equipped with optical slip rings, dispenses the cable as the ROV swims about below. Extended mission lifetime is available for ROVs with externally supplied power. Larger propulsion systems are sometimes needed to move the ROV through the water due to the drag of the larger cable, however this cable, for most applications is much smaller than its coaxial counterpart.

Many fiber optic telemetry systems for ROVs are simple compared to the long-haul undersea links. The mission stand-off range and total sensor bandwidth requirements are low enough that inexpensive components can be utilized. Short-wavelength LED transmitters coupled to multimode fibers and PIN photodiode receivers are adequate. For use as a simple design aid, figure 4 provides information on stand-off range as a function of data rate for full-duplex, fiber optic ROV telemetry links.

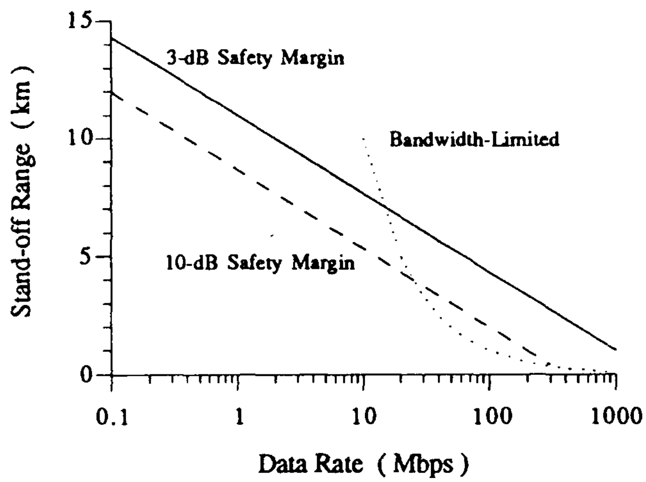

Figure 4. Stand-Off Range vs. Data Rate for LED / Multimode Fiber / PIN Receiver Systems

While the plot in figure 4 extends to 1000 Mbps, LED-based systems are only good to about 250 Mbps. This is considered the top end of performance for LEDs. The dotted curve labeled "Bandwidth-Limited" represents the maximum stand-off length attainable and must be used for data rates above 10 Mbps. Comparing figure 4 with figure 1, note the vast differences in range attainable between an LED / multimode fiber based system and a laser / single-mode fiber based system. At a data rate of 10 Mbps and using a 10-dB safety margin, the laser system yields 160 km compared to only about 5 km for the LED system. Of course, the decision of which component set to use is based on application, reliability, and cost.

NOSC has combined the duplex concept used for ROVs with the long-distance optical components employed by the telecommunications companies to demonstrate a long-distance, unrepeatered bidirectional link [13]. Using duplex wavelengths of 1.3 and 1.55 μm, transmission over more than 185 km has been demonstrated to date and efforts are being applied to extending that distance further, through the use of an optical preamplifier and wavelengths of 1.53 and 1.56 μm [14].

FIBER OPTIC SENSORS

The field of fiber optic sensors is exploding. Many designs are finding their way to undersea applications. An optical fiber is used as the sensing element and is also used to carry light to and from one or more sensors for remote sensing applications. Fiber used in telecommunications must be immune to external physical disturbances such as pressure and temperature that influence the propagation characteristics of the fiber. Microbending can cause severe losses in these fibers if not minimized or completely eliminated. The cable design protects the fiber against these changes. A fiber sensor applies the opposite approach and takes advantage of the high sensitivity a fiber has to external forces. A fiber sensor principally operates by the alteration of one or more of the characteristics of the light traveling through it. The amplitude or intensity, the polarization, the wavelength, or the relative phase of the light is changed in proportion to a physical perturbation applied to the sensor. In effect, the light is modulated by the physical field. To retrieve the information, a receiver must decode the modulated light signal.

Incoherent Sensors

Sensors are divided into two categories: incoherent and coherent sensors. Incoherent sensors represent the simplest, most inexpensive type. Figure 5 illustrates the fundamentals of an incoherent sensor. It consists of a light source, a transmission and sensor fiber, and a detector / receiver. Light from an incoherent, relatively broadband source is used. This can be a white-light source or a narrower band LED. In a simple implementation the sensor is part of a long fiber link. The light is carried from the source through the sensor and on to a detector. When an external, physical perturbation is applied to the sensor, the intensity of the light is diminished proportionately. In other designs, the light polarization is rotated due to the measurand and this in turn is converted, via a polarized filter, into an intensity change at the receiver.

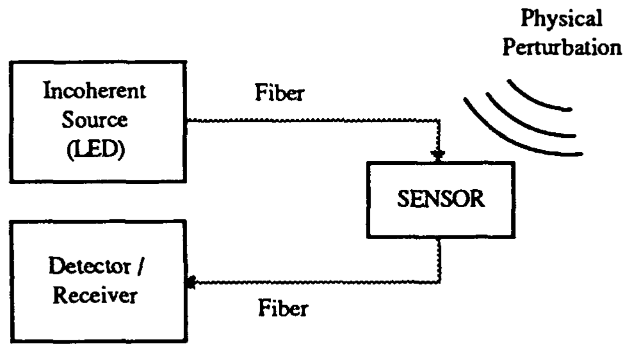

Figure 5. Incoherent Fiber Optic Sensor Diagram

Several schemes have been developed [15]. One is used to measure displacement [16]. The sensor is simply a moveable gap between two fiber endfaces. The gap bridges the entire link together. As displacement is applied, such as might be caused from an acoustic wave, the gap widens causing an increase in the coupling loss across the gap. This loss is translated to the detector in the form of a lower intensity. Lateral force can be measured with a fiber sensor. Microbend-induced attenuation is employed as the transduction mechanism. The sensor is comprised of a fiber sandwiched between two sets of opposing teeth. A lateral force is applied to one side, pushing the teeth together and slightly deforming the fiber. The deformation causes light traveling in the fiber to escape and this change in transmission is detected. A variation of this approach was used to measure deflection on an offshore oil platform [17]. An array of sensors was attached to the sides of the tension legs supporting the platform. The sensor data were time division multiplexed to a receiver which separated the information and decoded it. The multiplexing was achieved within the fiber network. The fibers were set in a parallel arrangement and the relative distances between each sensor automatically separated the return signals in time.

Temperature can be measured with a fiber optic sensor. A coating with a low thermal-expansion coefficient compared to glass is applied around a bare fiber. As the temperature varies the coating elongates and contracts. These forces cause microbending loss in the fiber and an associated light level change. A similar effect can be used to measure hydrostatic pressures. The pressure-induced stresses generate detectable microbending losses.

The Ocean Engineering Division at NOSC is involved in fiber optic sensors and has developed and patented a fiber-optic strain gauge [18]. Recall that optical fiber experiences stress corrosion in the presence of moisture and stress, ultimately causing premature fiber failure. It was necessary to design a device that could measure the residual strain inside an optical cable deployed in service underwater. The strain gauge uses an all-optical loop formed by the cable being measured. A resonant frequency is developed, which changes as the cable is strained. A strain resolution of 0.1% was achieved. Current work proposes to increase the finesse of the resonator by adding a small piece of erbium-doped fiber to the loop in an attempt to offset passive loop losses.

In a joint effort between NOSC and the U. S. Naval Postgraduate School, Monterey, an incoherent fiber optic angle encoder has been developed and patented [19]. The device can be used as a compass or to measure angular orientation of sonobuoys, hydrophones, and ROVs. Light is transmitted through an encoded disk impressing angular information onto the intensity or polarization of the light beam as the disk rotates. Angular resolution of 2 degrees was measured. Device miniaturization promises improved resolutions down to 0.5 degrees.

Coherent Sensors

While relatively simple to implement, incoherent sensors have limitations. They rely on stable source output powers. Resolution and repeatability is limited by random variations of the source. In contrast, coherent sensor techniques harness the ability to detect small changes in phase of a highly coherent lightwave. and are insensitive to power fluctuations. Figure 6 illustrates a simple coherent fiber optic sensor configuration.

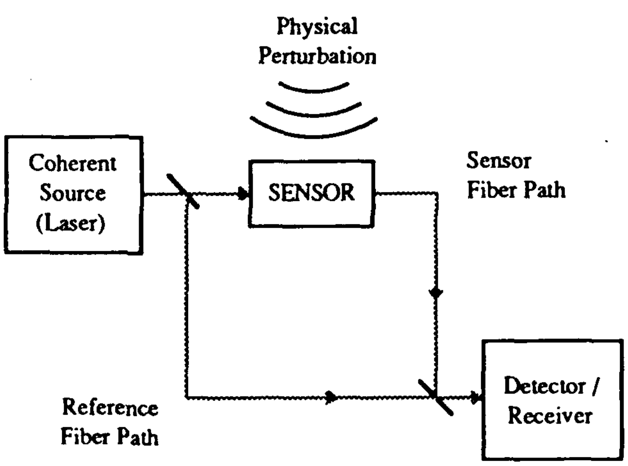

Figure 6. Coherent Fiber Optic Sensor Diagram

The sensor system is based on the optical interference between two coherent light beams. One beam passes through the sensor path of the system and the other passes through the reference path. As the phase in the sensor path changes due to some external perturbation, the resultant interference at the detector changes. When the two beams are in phase, the detector registers a maximum intensity and when the two are 180 degrees out of phase the two subtract to give a minimum intensity at the detector. Thus minute variations in phase shifts can be measured. Phase shifts in the sensor path can occur due to different effects. If the length of the sensor path changes, this results in a phase shift. The phase shift is proportional to the length change. Because the wavelength of light used in the sensor system is around 1 μm, the strain in a fiber can be measured very precisely. Displacements as small as 10^{-10} m have been measured. Strain-induced phase shifting forms the basis for many coherent sensor systems. Refractive index changes are also harnessed to produce phase shifts.

For undersea applications, coherent sensors are being developed for all-optical hydrophones [20]. One approach is to wrap the sensor fiber around a compliant mandrel. An incident acoustic wave deforms the mandrel and subsequently the fiber undergoes strain. This strain is converted into a detectable phase shift. Encouraging results have been reported in the low frequency band. At a frequency of 1 kHz, a minimum pressure response of 30 dB RE 1μPa has been measured. The response is very flat from 10 Hz -10 kHz. For comparison, an H56 piezoelectric hydrophone gives about 28 dB RE 1μPa at 1 kHz, but its performance is worse than the optical hydrophone at lower frequencies. The expected theoretical performance of the optical hydrophone is 0 dB RE 1μPa [14].

The Navy is investing heavily in fiber optic sensor research. All-optical sensors offer more than just potential improvements in sensitivity. The low loss and high bandwidth of the fiber allows the fiber sensors to be deployed to remote locations and applied to high speed sensing. The signal remains optical and obviates the need for transmitting electrical current. The geometric versatility allows multiple-fiber sensor networks at a reduced size. The fibers are safe to deploy in combustible areas because they do not cause sparks. The fibers are not susceptible to EMI and therefore can be used around high magnetic fields.

The level of interest in fiber optic sensors grows as the number of designs dramatically increases. Within the Navy, most of the fiber optic sensor research is being conducted at NOSC, the NPG School, NRL, and NUSC. Outside agencies include AT&T, Honeywell, JPL, Litton, Martin-Marrietta, and the NASA/Lewis Research Center.

REFERENCES

[1] P. K. Runge and P. R. Trischitta, " The SL Undersea Lightwave System", IEEE Journal on Selected Areas in Communications, Vol. SAC-2, No. 6, pp. 784-793, November 1984.

[2] P. A. Dawson and K. D. Fitchew, "Repeater Design Requirements", British Telecommunications Engineering, Vol. 5, pp. 97-103, July 1986.

[3] S. Shibata, M. Horiguchi, S. Mitachi, and T. Manabe, "Prediction of loss minima in infrared optical fibers", Electron. Lett., pp. 775-777, 1981.

[4] B. Bendow, "Mid-IR fiber optics technology: A study and assessment," NOSC Final Report CR 243, February 1984.

[5] T. Okoshi, "Recent advances in coherent optical fiber communication systems", J. Lightwave Tech., Vol. LT-5, pp. 44-52, 1987.

[6] Grasso, G., Cheung, N.K. , et. al.,"An 11 Gbit/sec 260 km transmission experiment using a directly modulated DFB laser with two ER-doped amplifiers and clock recovery", Proc. of ECOC (Gothenburg), Postdeadline Session Paper PDA 10, 1989.

[7] K. Aida, H. Masuda, and A. Takada, "Long-span IM/DD Transmission System Experiment using High-Efficiency EDF Amplifiers", Proceedings of Optical Amplifiers Topical Meeting, Paper TuC5, pp.164-167, 6-8 August 1990.

[8] Y. K. Park, J-M P. Delavaux, R. E. Tench, and T. W. Cline, "1.7 Gb/s-419 km Transmission Experiment using a Shelf-Mounted FSK Coherent System and Packaged Fiber Amplifier Modules", Proceedings of Optical Amplifiers Topical Meeting, Paper TuC4, pp.160-163, 6-8 August 1990.

[9] K. J. Blow and N. J. Doran, "Long-distance amplified soliton systems: a novel modulation concept", IEEE Proceedings on the Optical Fiber Conference '91, Paper ThL3, 18-22 February 1991.

[10] J. J. Keller, "New AT&T System May Sharply Boost Capacity of Marine Transmission Cables", Wall Street Journal, p. B4, 2 July 1990.

[11] M. E. Kono and M. R. Brininstool, "Towards a Universal Design for ROV Telemetry via Fiber Optics", Proc. of International Telemetering Conference, Vol.14, pp. 523-535, 1983.

[12] M. Kono, M. Brininstool, and S. Cowen, "Fiber Optic Telemetry for the REGAL Torpedo", NOSC Technical Report TR 920, April 1984.

[13] M. R. Brininstool, "104-km Unrepeatered Bidirectional Fiber Optic Demonstration Link", NOSC Technical Report TR 1185, May 1987.

[14] M.R. Brininstool, S.J. Cowen, W.H. Marn, and M.C. Scallon, "Long-Distance Repeaterless Duplex Fiber-Optic Demonstration System", NOSC Technical Report TR 1411, February 1991.

[15] R. P. De Paula and E. L. Moore, "Fiber Optic Sensor Overview", Proc. of SPIE, Vol. 566, Fiber Optic and Laser Sensors III, [566-01], 1985.

[16] N. Lagakos, "Multimode optical fiber displacement sensor", Applied Optics, Vol. 20, p. 167, 1981.

[17] S. A. Kingsley, "Distributed Fiber Optic Sensors: An Overview", Proc. of SPIE, Vol. 566, Fiber Optic and Laser Sensors III, [566-68], 1985.

[18] M. R. Brininstool, "Measuring longitudinal strain in optical fibers", Optical Engineering, Vol. 26, No. 11, pp. 1112-1119, November 1987.

[19] J. T. Newmaster, M. R. Brininstool, T. Hofler, S. L. Garrett, "Remote fiber optic sensors for angular orientation", Proc. of SPIE, Vol. 838, Fiber Optic and Laser Sensors V, pp. 28-38, August 1987.

[20] J. A. Bucaro, E. F. Carome, and H. D. Dardy, "Fiber optic hydrophone", J. of Acoustic. Soc. Am., Vol.62, No. S1, pp. 1302-1304, 1977

OCEANIC APPLICATIONS OF FIBER OPTICS

Michael R. Brininstool

Naval Ocean Systems Center
Ocean Engineering Division
San Diego, CA 92152

ABSTRACT

Oceanic applications of fiber optics are rapidly advancing, following on the heels of the more mature land-based telecommunications systems. While many features of each arena are similar, undersea fiber systems demand unique capabilities. Components capable of withstanding brutal hydrostatic pressures and near freezing temperatures had to be developed. This paper highlights undersea fiber optic systems and their features. It focuses on long distance telecommunications and remotely-operated-vehicle (ROV) links. Also addressed is the emerging technology of fiber optic sensors. These designs use the fiber as a sensing element to detect such variables as displacement, pressure, temperature, strain, and rotation.

INTRODUCTION

Fiber optics is increasingly becoming the media of choice in a wide assortment of undersea applications. The main thrust of development efforts are directed toward fiber optic telemetry and sensors. Several distinct advantages over conventional wire technology are exploited. Fibers possess very low intrinsic attenuation of the optical power traveling down the waveguide. With the common silica-glass based fiber used today, attenuations as low as 0.2 dB/km are achievable. This compares dramatically to coaxial transmission lines where the attenuation varies as a function of carrier frequency and can range from 4 to 100 dB/km for moderate bandwidths of 100 MHz.

Optical fibers have extremely large bandwidth-length products. The single-mode fibers, at the high performance end of the fiber product line, have bandwidth-length products as high as 800 GHz-km. Even the more modest multimode fibers can provide 1 GHz-km. These values translate into huge bandwidth-limited transmission distances. However, for most applications, it is the fiber attenuation, not the bandwidth that usually limits the ultimate distance a signal can be transmitted. For trans-oceanic communications links, the attenuation-limited distance determines how many repeaters are required and thus directly influences the system cost. The latest fiber optic transatlantic link was brought on-line in November 1989. Known as TAT-8, the 6100-km system bridges the east coast of the United States to Great Britain and France with a telephone system capable of simultaneously transmitting 40,000 digitized voice channels at a data rate of 280 Mbps [1]. The system requires only 125 repeaters, spaced 50 km apart. Future systems will be able to extend that spacing to 100-150 km. TAT-7 was the last transatlantic coaxial cable system placed in service. In comparison, the repeater spacing was only about 10 km and the cable carried 4200 analog phone circuits.

Fiber optics will continue to play a large role in undersea links, increasing channel capacity and repeater spacing distance. Both of these improvements provide great cost savings. As the number of voice channels grows the cost per channel diminishes. The TAT-8 system cost \$360 million, or \$9,000 for each of its 40,000 voice lines. Capacity expansion by at least a factor of 20 is anticipated over the next five years. Each repeater cost about \$800,000 for TAT-8. New optical amplifier technology aims at reducing both the number, complexity, and cost of a repeater while improving the reliability.

Small size and light weight are two other outstanding features optical fiber offers to undersea links. As an example, an expendable, underwater tether cable for ROV telemetry has a diameter of only 900 μm and weighs less than 1 kg/km in air and is nearly neutrally buoyant in water. A coaxial cable with comparable bandwidth is about 30 mm in diameter and weighs over 1110 kg/km. For ROVs, the size and weight savings means reduced cable drag, extended mission lifetime, and enhanced packing density of the spooled cable housed within the vehicle.

TELEMETRY APPLICATIONS

This section addresses a few applications of fiber optics applied to undersea telemetry. Included are long-haul systems and ROV communication links.

Long-Haul Systems

Most of the fiber deployed for long-haul trans-oceanic systems is used for carrying telephone channels. Shared on the telephone lines are facsimile and computer data and, to a growing extent, video transmission. AT&T is playing a significant role in installing trans-oceanic links. In addition to the TAT-8 system, another trans-Atlantic route, TAT-9, is expected to be completed in December 1991. Taking advantage of newer 1.55-μm laser technology, it will carry 80,000 voice channels over three 560-Mbps fiber pairs, with 100-km repeater spacings. Another route, TRANSPAC-3, or TPC-3, will run from Hawaii to Japan via Guam. All current designs use similar approaches. To achieve long repeater spacings the fiber link consists of long-wavelength high-powered laser-diode transmitters, low-loss single-mode optical fibers, and high-sensitivity PIN-FET receivers.

In addition to power budget considerations, it is also important that the fiber system maintain adequate bandwidth over the repeater span. Laser diodes have very high modulation bandwidths, with some capable of 10 GHz. The coherence of the laser aids in maximizing the fiber bandwidth. Its narrow spectral linewidth minimizes pulse spreading due

to chromatic dispersion in the fiber. The single-mode fiber bandwidth is virtually unlimited when used with optimized laser sources. Receiver bandwidth is kept close to the system bandwidth to reject out of band electronic noise. This optimizes the signal-to-noise ratio and the sensitivity.

Because the noise bandwidth influences receiver sensitivity, repeater spacings are dependent on the required data rate of the system. As the system data rate increases the span length decreases since more incident optical power is required at the receiver to overcome the noise. This is illustrated in Figure 1, plotting repeater spacing as a function of data rate for a fiber link comprised of a laser transmitter, a single-mode fiber, and a PIN-FET receiver. The two curves represent results from using two different values for optical safety margin. The safety margin insures against future link degradations due to laser output power reduction, increased fiber attenuation, and potential repairs. The margin is added to the total optical loss allocated for fiber attenuation, splice and connector loss, and other passive component losses incurred along the path. A 3-dB safety margin is considered minimal, especially for undersea applications and 10-dB margin is more practical. The TAT-8 system employs a 9-dB margin: 2 dB allowance for repair, 4 dB for laser ageing, and 3 dB for an end of life margin [2].

Figure 1 is used to quickly determine the maximum data rate capacity a fiber link can manage if the span distance is given. For example, supposed a repeaterless link is to be installed over 160 km, approximately 100 miles. For a 10-dB safety margin, the data rate limit is about 10 Mbps. This is equivalent to roughly 150 uncompressed voice channels. The figure can also be used conversely to determine repeater spacing for a link given the system data rate.

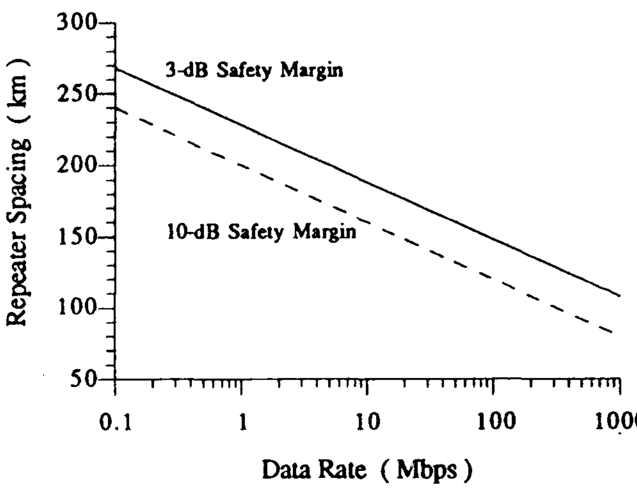

Figure 1. Repeater Spacing for Laser / Single-mode Fiber / PIN-FET Receiver Systems

The repeater for an undersea link houses the receiver, transmitter, power circuitry, and associated supervisory control electronics. The control electronics monitors the health of the repeater components and notifies a master supervisor of any trouble. For higher reliability, redundancy is used. The TAT-8 system uses six optical fibers in its cable. Two pairs are active and one pair is on standby. The repeater has three extra lasers that can be switched remotely by the master supervisor in the event of a laser and / or fiber failure. The repeater electronics are maintained at one atmosphere pressure. The housing seals around the ends of the cable terminations.

Submarine Cable

The underwater fiber optic cable must meet several stringent requirements to maintain the integrity of the fiber. The cable must protect the fiber from longitudinal stresses, moisture intrusion, large hydrostatic pressure exposure, and extreme thermal excursions.

The fiber element is fundamentally very strong. However, microscopic defects along the surface of the fiber weaken the element considerably. Adding to this problem is moisture. In the presence of stress and moisture, the flaws in the fiber surface grow, further weakening the fiber due to stress corrosion. If allowed to continue, the flaw will ultimately sever the fiber. Although the fiber used for undersea cables is typically much stronger than that used in terrestrial cable, it still must be protected. The fibers are normally embedded in a stiff, matrix material, such as Hytrel™, which forms a bonded unit. Units housing multiple fibers place the fibers in a helix around a central steel "king" wire. Any axial load applied to the unit is taken up first by the king wire. Kevlar™ is another strength member used commonly in cables. Additional strengthening is added depending on the expected loads the cable will undergo during installation and service.

The TAT-8 system uses two types of cables: one for deep water and one for shallow water service. The deep water cable has a layer of galvanized steel wires enclosing the fiber optic unit in a pressure tolerant "cage". A thin copper layer is welded around the steel layer. The copper is used to carry the electrical current necessary to power the repeaters. The combination of the copper and steel layer provides a water-tight pressure-tolerant chamber for the fibers. Since the cable is manufactured on the surface, the fibers remain at one atmosphere for the entire system lifetime. This pressure-tolerant chamber is vital to the survival of the fiber elements. It eliminates the water intrusion, thereby reducing stress corrosion problems. The steel wires also significantly increase the tensile strength of the cable.

The optical transmission integrity of the fibers is also well preserved. If exposed to high levels of hydrostatic pressure, the fiber unit will begin to buckle. This buckling attributes to microbending attenuation in the fibers. If severe, the fibers can go completely dark. The steel strength members prevent hydrostatic pressure from effecting the fiber unit. Under pressure the steel wires lock up, forming a rugged barrier. The copper layer serves as a water and hydrogen barrier. Hydrogen, from filling compounds in the cable, has been shown to diffuse into the fiber increasing optical transmission losses due to absorption.

Thermal-induced contractions in the fiber unit at low temperatures can also cause microbend attenuation. This contraction is restricted by the helix within the Hytrel™ matrix and by the steel strength members. Surrounding the

strength members is a thick layer of low density polyethylene. This layer serves as the insulation for the electrical current. A sea-water ground return is used and the current must be isolated.

The shallow water cable has thick galvanized steel armor wires surrounding the deep water cable structure. This armoring protects the cable against accidental fishing trawler damage and abrasion caused by continual movement across coral and rocks.

The Future of Long Haul

There are several exciting technologies emerging that promise great improvements for long-haul undersea links. They are aimed at extending the repeater spacing and channel data rate capacity. Four significant technologies discussed here are mid-infrared fiber optics, coherent fiber optics, optical fiber amplifiers, and soliton communications.

The TAT-8 system uses fiber made from silica glass and transmits data over the fiber with laser diodes emitting in the 1.3-µm wavelength range. This wavelength was chosen because it corresponds to a low-attenuation, low-dispersion window in silica glass. Also the 1.3-µm laser technology was the most mature at the time of development. Since then the 1.55-µm wavelength has become the color of choice. The glass exhibits a lower attenuation at 1.55 µm than at 1.3 µm and thus data can be sent further. To maintain the high bandwidth requirement, fiber with the minimum dispersion wavelength shifted to 1.55 µm is used. Figure 1 was generated based on a 1.55-µm laser transmitter. This represents the wavelength for the lowest attenuation, 0.2 dB/km, attainable using silica-based glass. New types of fiber made from heavy-metal fluoride glass are being developed. When used at wavelengths of 2.7 µm, these fibers have the potential for attenuations as low as 0.001 dB/km [3]. Researchers at the Naval Research Lab, AT&T, and Corning have independently achieved losses of 1 dB/km, down from 20 dB/km just four years ago [4]. The rapid improvements are attributable to applying the lessons learned in making low-loss silica fiber over the last twenty years. Many obstacles must still be overcome. Suitable sources and detectors must be developed to operate in the mid-infrared region. Detectors must be cryogenically cooled to achieve high sensitivities due to thermal-generated noise currents in the detector at these wavelengths. The fiber material has low strength and a low melting temperature compared to silica. Fluoride glass has a very low melting temperature, 300 °C, compared to over 1000 °C for silica. The fluoride tends to be hygroscopic and readily absorbs water.

Presently, all undersea long-haul fiber systems use intensity modulation (IM) of the lasers to transmit digital data. Direct detection (DD) of the signals converts the intensity into electrical current. Coherent fiber optic communication systems (COFOCS) utilize the coherent nature of spectrally pure, single-longitudinal mode lasers. Information is impressed on the phase of the lightwave instead of the intensity, as is done with direct-detection systems. At the receiver, optical heterodyne mixing of the signal with a local optical oscillator provides improved sensitivities close to the quantum limit. Improvements in sensitivity of 5 - 20 dB can be achieved over direct detection schemes [5]. This translates into detecting weaker signals and being able to extend the repeater spacing distance. Receiver channel selectivity is another benefit COFOCS provides. More channels can be packed together on a single fiber line by separating them at slightly different optical frequencies, thereby increasing the ultimate bandwidth capacity of the fiber. Many technical issues are being addressed with COFOCS. The heterodyne receiver is very sensitive to the polarization state of both the local oscillator and the signal fields. Random phase fluctuations of the transmitter also cause degraded reception.

Probably the most publicized technical advance for extending repeater distance is in the area of optical fiber amplifiers. Fiber amplifiers are inserted directly into the optical path and provide gain to the signal. A coil of fiber, typically 10-100 meters long, is lightly doped with trivalent rare-earth ions such as erbium. The fiber coil is then excited with a laser-diode pump source using a WDM to couple the pump power into the coil. The pump power raises the rare-earth ions in the fiber coil to an excited metastable state of population inversion. Under this condition, according to quantum electronics, a signal passing through the coil with a wavelength equivalent to the transition between excited and ground states experiences a net gain due to stimulated emission. The principles are similar to gain developed in optically pumped lasers. Fiber amplifiers have many outstanding features. The fiber geometry offers unique advantages. The fiber is easily interfaced to the transmission line fiber. Fusion splices give low-loss, low-reflection coupling. The pump and signal powers are confined to a very small core area over an extended interaction length. This provides for efficient pump absorption over long lengths. The fiber gain is polarization insensitive. Fiber amplifiers are potentially more reliable and smaller than their opto-electronic counterparts. Unlike opto-electronic repeaters, the fiber amplifiers are essentially bit rate transparent. Experiments have shown a limit in the Tbps range [6]. Limitations in long-distance systems with multi-repeater fiber amplifiers include optical noise build-up as the light passes through the amplifier cascade chain and fiber dispersion which limits the data rate capacity.

The future will see rapid advances in gain performance and packaging of fiber amplifiers as they become widely adopted for an assortment of long-distance, multi-access distribution network, and sensor applications. One recent report stated fiber amplifier repeater gains of 55 dB were achieved. The fiber amplifier was employed in a laboratory IM/DD system and a 1.8-Gbps nonrepeatered transmission over a length of 308 km was accomplished [7]. Long-distance links employing both coherent detection and fiber amplifiers have been reported. One experiment at AT&T achieved 1.7-Gbps transmission over 419 km using an FSK coherent system with fiber amplifiers [8].

Communications experiments utilizing the physics of optical solitons are being conducted. As fiber amplifiers help to extend the power-limited distances for undersea links, the systems become bandwidth or dispersion-limited. The

narrow optical pulses spread into each other and become indistinguishable after many hundreds of kilometers. Soliton communications promises to reduce the dispersion limitation significantly. Solitons are specially shaped light pulses that take advantage of nonlinear properties of the fiber through an effect known as self-phase modulation (SPM). SPM counters the effects of dispersion so that the pulse width is maintained over extremely long distances. Neighboring pulse interactions, pulse shaping, and optimum repeater spacing are issues currently being studied. Recent efforts have demonstrated soliton communications using fiber amplifiers over trans-oceanic distances at 10 Gbps [9]. AT&T has joined with KDD of Japan in a venture to place a 9,000-km undersea link using solitons and fiber amplifiers between Seattle and Tokyo by 1996. The system is projected to carry 700,000 voice channels at a rate of 5 Gbps [10].

While several years are necessary before any of these new technologies are fully transitioned from the laboratories to the field, it is interesting to witness their development. Less than two years have past since the first fiber amplifier milestones were reported and already four companies offer turn-key fiber amplifiers. However, with price tags of $15,000 - $40,000 they are still mostly suitable for research applications.

ROV Telemetry

For years remotely operated vehicles, ROVs, have aided in undersea tasks including offshore platform inspection and repair, weapon recovery, cable replacement, and rescue. They are also helpful in scientifically characterizing ocean parameters using sensitive equipment to measure salinity, current, temperature, pressure, and depth. The ROVs are tethered to the support vessel with an umbilical cable which carries power and control signals down to the vehicle and retrieves vehicle data. This data takes the form of video images, high-resolution acoustic images, vehicle status, and computer commands. Fiber optics advances the capabilities of the ROV through its outstanding features of low loss, high bandwidth, and small size. The low loss allows the vehicle to have a greatly extended mission stand-off range. In the area of mine neutralization and under-ice exploration this is essential. The high bandwidth feature allows the vehicle to support sophisticated data collection equipment such as multiple cameras, stereoscopic cameras, and high-resolution sonar. It also allows much of the computer software needed for autonomous maneuvers to be handled and housed in a computer on board the support vessel. This reduces vehicle weight, power consumption, and cost. The small size allows a spool of fiber cable to be housed and deployed from the vehicle. For self-powered ROVs, operating solely on batteries, the fiber cable can be quite small and expendable, thereby maximizing packing density.

The NOSC Connection

The Ocean Engineering Division at NOSC, San Diego has pioneered ROV technology. It continues to be on the leading edge of advanced vehicle development. In the field of fiber optics for ROV telemetry it has also excelled [11]. Over the past ten years it has advanced the state of the art in several significant areas.

Early in the 1980's NOSC demonstrated the first fiber-optically guided torpedo [12]. The successful demonstration was the culmination of several years of research and development effort in producing a high-speed underwater fiber optic link that could remotely guide a torpedo. The advantages were clear: faster target acquisition rates, lighter torpedo weight, and transfer of the torpedo computer hardware to the support vessel. To achieve this, many fiber-optic components unique to undersea vehicles and not available at the time had to be developed.

Figure 2 depicts a simple block diagram of a typical fiber optic data link for a ROV. The link is divided into four major sections: the topside optics residing on the support vessel, the ROV optics residing inside the one-atmosphere electronics bottle of the vehicle, the optical pressure penetrator, and the fiber optic cable. As is seen, one feature distinguishing this system from a point-to-point system is that the link is bi-directional. The downlink transmits command and control data from the support vessel to the ROV. These commands can originate from an operator or a computer. The uplink sends ROV sensor data back to the support vessel to be processed and stored. Together the two links form a closed control loop for vehicle manipulation.

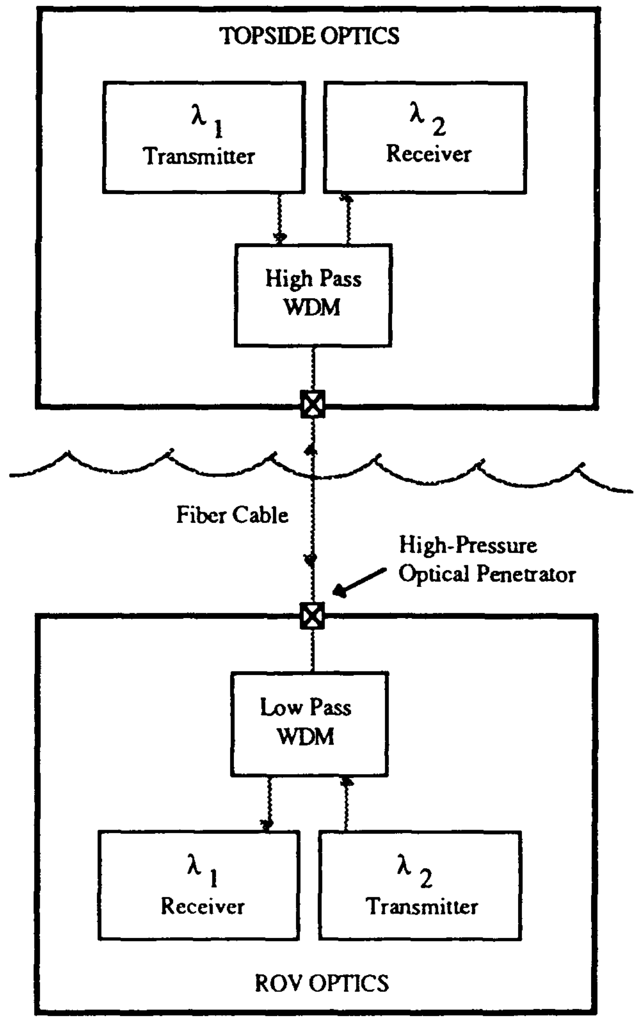

Figure 2. Block Diagram of ROV Fiber Optic Duplex Telemetry System

Bidirectional communication is performed over a single fiber element, making the system full duplex. The duplexing is achieved optically by using two separate wavelengths of light. These wavelengths are labeled λ_1 and λ_2 in the figure. The concept is referred to as wavelength division multiplexing and is similar to frequency division multiplexing of two different electronic frequencies.

At the heart of the duplexing scheme are two wavelength division multiplexers or WDMs. The WDM serves three functions: to inject outgoing light from the local transmitter into the fiber transmission cable, to extract incoming light from the distant transmitter and direct it to the local receiver, and to isolate the light signals between the local transmitter and receiver. The injection and extraction functions must be done efficiently with a minimal optical loss and the isolation must be high enough to prevent unwanted crosstalk between the two channels. These functions are achieved using optical fiber pigtails, graded-index (GRIN) lenses, and dichroic interference filters. Figure 3 illustrates the type of WDM built at NOSC. This approach is now a widely accepted method for producing WDMs with large channel isolations. The WDM is fabricated by sandwiching the dichroic filter between two GRIN lenses. The filter has a transmission characteristic that passes one wavelength and reflects the other. As is shown, light at λ_1 from the local transmitter is coupled via a fiber into the first lens. It reflects off of the filter and is directed into the transmission line fiber. Light coming from the distant transmitter at λ_2 enters the first lens, passes through the filter, passes through the second lens, and is directed via a fiber to the local receiver. The lenses provide the efficient coupling, less than 1-dB loss, and the filter provides the isolation, greater than 60 dB, between λ_1 and λ_2. For a complete duplex system, two complimentary WDMs are needed, one with a low-pass filter and one with a high-pass filter.

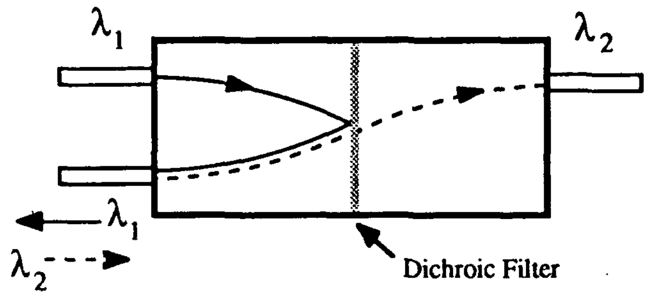

Figure 3. Optical Design for a Full-Duplex Wavelength Division Multiplexer

The low data rates and relatively short distance of the first demonstration link obviated the need for single-mode fiber and laser transmitters. The system used a multimode fiber cable, LED transmitters, and PIN photodiode receivers. NOSC built their own WDMs to operate at 0.83 and 1.06 µm, the wavelengths of light most commonly available from LED manufacturers at the time.

Another development necessary for a successful fiber optic ROV telemetry link is an optical, high-pressure bulkhead penetrator. This device efficiently transfers light from the cable into the electronics bottle and seals the bottle against the high ambient ocean pressure. GRIN lens techniques are used to collimate light across the pressure barrier. NOSC has been a world leader in developing these optical penetrators and holds several U. S. patents for their designs.

Critical to the success of the ROV telemetry link is the survival of the fiber cable in the harsh ocean environment. The cable must withstand crushing ambient pressures and near freezing temperatures. In addition, for fiber-guided torpedoes, it must tolerate high cable payout speeds. NOSC has been the leader in developing undersea fiber cable designs for fiber optic ROV telemetry. For expendable tethers, such as those used for torpedoes, the cable carries no electrical power. The objective is to build the smallest diameter cable that can survive. The design is an epoxy / fiber-glass reinforced matrix surrounding the buffered fiber. The microcable is slightly larger than the buffered fiber but capable of survival, both physically and optically, at high pressures and low temperatures.

Extremely high packing density in a free-standing spool is achieved with the small cable. This allows long cable lengths to be stowed compactly. The spool is placed inside the vehicle and the cable is deployed in a center pull-out technique along the spool's longitudinal axis as the vehicle moves through the water. A winding machine has been developed at NOSC to facilitate the spooling of the microcable. The cable coils are precision wound in a close-packed geometry and held in place by application of a low-bond-strength adhesive. As the cable is wound onto the spool a 360-degree pretwist is applied that opposes the twist that occurs during payout. This results in a torsion-free cable during deployment, eliminating the tendency for the cable to hackle should it go slack in the water column.

Most ROVs require a reusable tether cable containing electrical wires for power transport as well as optical fibers. The power is used for propulsion, lights for the cameras, sensors, and electronics. These hybrid cables are considerably larger than the expendable microcables. In most instances the cable is stored and deployed off of the support vessel. A cable winch, equipped with optical slip rings, dispenses the cable as the ROV swims about below. Extended mission lifetime is available for ROVs with externally supplied power. Larger propulsion systems are sometimes needed to move the ROV through the water due to the drag of the larger cable, however this cable, for most applications is much smaller than its coaxial counterpart.

Many fiber optic telemetry systems for ROVs are simple compared to the long-haul undersea links. The mission stand-off range and total sensor bandwidth requirements are low enough that inexpensive components can be utilized. Short-wavelength LED transmitters coupled to multimode fibers and PIN photodiode receivers are adequate. For use as a simple design aid, figure 4 provides information on stand-off range as a function of data rate for full-duplex, fiber optic ROV telemetry links.

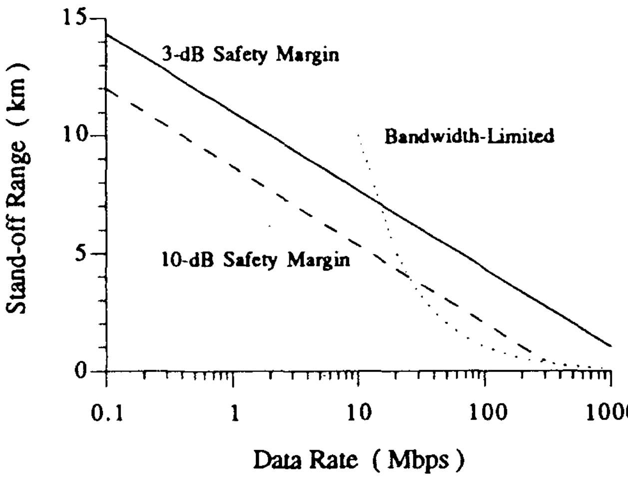

Figure 4. Stand-Off Range vs. Data Rate for LED / Multimode Fiber / PIN Receiver Systems

While the plot in figure 4 extends to 1000 Mbps, LED-based systems are only good to about 250 Mbps. This is considered the top end of performance for LEDs. The dotted curve labeled "Bandwidth-Limited" represents the maximum stand-off length attainable and must be used for data rates above 10 Mbps. Comparing figure 4 with figure 1, note the vast differences in range attainable between an LED / multimode fiber based system and a laser / single-mode fiber based system. At a data rate of 10 Mbps and using a 10-dB safety margin, the laser system yields 160 km compared to only about 5 km for the LED system. Of course, the decision of which component set to use is based on application, reliability, and cost.

NOSC has combined the duplex concept used for RO\ with the long-distance optical components employed by the telecommunications companies to demonstrate a long-distance, unrepeatered bidirectional link [13]. Using duplex wavelengths of 1.3 and 1.55 μm, transmission over more than 185 km has been demonstrated to date and efforts are being applied to extending that distance further, through the use of an optical preamplifier and wavelengths of 1.53 and 1.56 μm [14].

FIBER OPTIC SENSORS

The field of fiber optic sensors is exploding. Many designs are finding their way to undersea applications. An optical fiber is used as the sensing element and is also used to carry light to and from one or more sensors for remote sensing applications. Fiber used in telecommunications must be immune to external physical disturbances such as pressure and temperature that influence the propagation characteristics of the fiber. Microbending can cause severe losses in these fibers if not minimized or completely eliminated. The cable design protects the fiber against these changes. A fiber sensor applies the opposite approach and takes advantage of the high sensitivity a fiber has to external forces. A fiber sensor principally operates by the alteration of one or more of the characteristics of the light traveling through it. The amplitude or intensity, the polarization, the wavelength, or the relative phase of the light is changed in proportion to a physical perturbation applied to the sensor. In effect, the light is modulated by the physical field. To retrieve the information, a receiver must decode the modulated light signal.

Incoherent Sensors

Sensors are divided into two categories: incoherent and coherent sensors. Incoherent sensors represent the simplest, most inexpensive type. Figure 5 illustrates the fundamentals of an incoherent sensor. It consists of a light source, a transmission and sensor fiber, and a detector / receiver. Light from an incoherent, relatively broadband source is used. This can be a white-light source or a narrower band LED. In a simple implementation the sensor is part of a long fiber link. The light is carried from the source through the sensor and on to a detector. When an external, physical perturbation is applied to the sensor, the intensity of the light is diminished proportionately. In other designs, the light polarization is rotated due to the measurand and this in turn is converted, via a polarized filter, into an intensity change at the receiver.

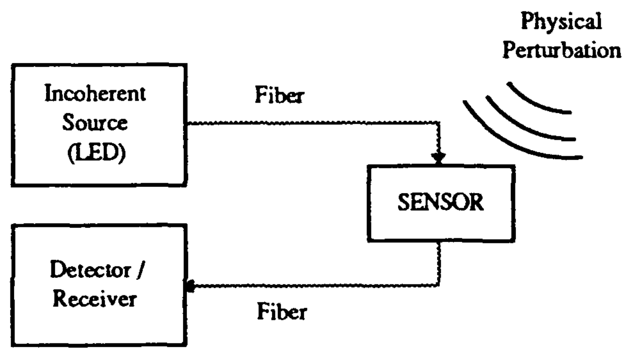

Figure 5. Incoherent Fiber Optic Sensor Diagram

Several schemes have been developed [15]. One is used to measure displacement [16]. The sensor is simply a moveable gap between two fiber endfaces. The gap bridges the entire link together. As displacement is applied, such as might be caused from an acoustic wave, the gap widens causing an increase in the coupling loss across the gap. This loss is translated to the detector in the form of a lower intensity. Lateral force can be measured with a fiber sensor. Microbend-induced attenuation is employed as the transduction mechanism. The sensor is comprised of a fiber sandwiched between two sets of opposing teeth. A lateral force is applied to one side, pushing the teeth together and slightly deforming the fiber. The deformation causes light traveling in the fiber to escape and this change in transmission is detected. A variation of this approach was used to measure deflection on an offshore oil platform [17]. An array of sensors was attached to the sides of the tension legs supporting the platform. The sensor data were time division multiplexed to a receiver which separated the information and decoded it. The multiplexing was achieved within the fiber network. The fibers were set in a parallel arrangement and the relative distances between each sensor automatically separated the return signals in time.

Temperature can be measured with a fiber optic sensor. A coating with a low thermal-expansion coefficient compared to glass is applied around a bare fiber. As the temperature varies the coating elongates and contracts. These forces cause microbending loss in the fiber and an associated light level change. A similar effect can be used to measure hydrostatic pressures. The pressure-induced stresses generate detectable microbending losses.

The Ocean Engineering Division at NOSC is involved in fiber optic sensors and has developed and patented a fiber-optic strain gauge [18]. Recall that optical fiber experiences stress corrosion in the presence of moisture and stress, ultimately causing premature fiber failure. It was necessary to design a device that could measure the residual strain inside an optical cable deployed in service underwater. The strain gauge uses an all-optical loop formed by the cable being measured. A resonant frequency is developed, which changes as the cable is strained. A strain resolution of 0.1% was achieved. Current work proposes to increase the finesse of the resonator by adding a small piece of erbium-doped fiber to the loop in an attempt to offset passive loop losses.

In a joint effort between NOSC and the U. S. Naval Postgraduate School, Monterey, an incoherent fiber optic angle encoder has been developed and patented [19]. The device can be used as a compass or to measure angular orientation of sonobuoys, hydrophones, and ROVs. Light is transmitted through an encoded disk impressing angular information onto the intensity or polarization of the light beam as the disk rotates. Angular resolution of 2 degrees was measured. Device miniaturization promises improved resolutions down to 0.5 degrees.

Coherent Sensors

While relatively simple to implement, incoherent sensors have limitations. They rely on stable source output powers. Resolution and repeatability is limited by random variations of the source. In contrast, coherent sensor techniques harness the ability to detect small changes in phase of a highly coherent lightwave. and are insensitive to power fluctuations. Figure 6 illustrates a simple coherent fiber optic sensor configuration.

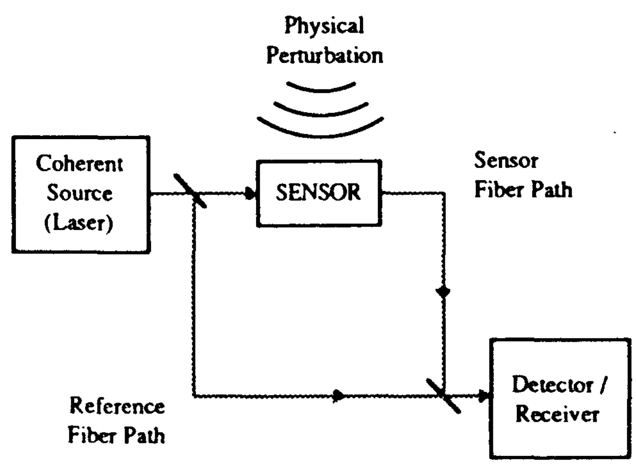

Figure 6. Coherent Fiber Optic Sensor Diagram

The sensor system is based on the optical interference between two coherent light beams. One beam passes through the sensor path of the system and the other passes through the reference path. As the phase in the sensor path changes due to some external perturbation, the resultant interference at the detector changes. When the two beams are in phase, the detector registers a maximum intensity and when the two are 180 degrees out of phase the two subtract to give a minimum intensity at the detector. Thus minute variations in phase shifts can be measured. Phase shifts in the sensor path can occur due to different effects. If the length of the sensor path changes, this results in a phase shift. The phase shift is proportional to the length change. Because the wavelength of light used in the sensor system is around 1 μm, the strain in a fiber can be measured very precisely. Displacements as small as 10^{-10} m have been measured. Strain-induced phase shifting forms the basis for many coherent sensor systems. Refractive index changes are also harnessed to produce phase shifts.

For undersea applications, coherent sensors are being developed for all-optical hydrophones [20]. One approach is to wrap the sensor fiber around a compliant mandrel. An incident acoustic wave deforms the mandrel and subsequently the fiber undergoes strain. This strain is converted into a detectable phase shift. Encouraging results have been reported in the low frequency band. At a frequency of 1 kHz, a minimum pressure response of 30 dB RE 1μPa has been measured. The response is very flat from 10 Hz -10 kHz. For comparison, an H56 piezoelectric hydrophone gives about 28 dB RE 1μPa at 1 kHz, but its performance is worse than the optical hydrophone at lower frequencies. The expected theoretical performance of the optical hydrophone is 0 dB RE 1μPa [14].

The Navy is investing heavily in fiber optic sensor research. All-optical sensors offer more than just potential improvements in sensitivity. The low loss and high bandwidth of the fiber allows the fiber sensors to be deployed to remote locations and applied to high speed sensing. The signal remains optical and obviates the need for transmitting electrical current. The geometric versatility allows multiple-fiber sensor networks at a reduced size. The fibers are safe to deploy in combustible areas because they do not cause sparks. The fibers are not susceptible to EMI and therefore can be used around high magnetic fields.

The level of interest in fiber optic sensors grows as the number of designs dramatically increases. Within the Navy, most of the fiber optic sensor research is being conducted at NOSC, the NPG School, NRL, and NUSC. Outside agencies include AT&T, Honeywell, JPL, Litton, Martin-Marrietta, and the NASA/Lewis Research Center.

REFERENCES

[1] P. K. Runge and P. R. Trischitta, " The SL Undersea Lightwave System", IEEE Journal on Selected Areas in Communications, Vol. SAC-2, No. 6, pp. 784-793, November 1984.

[2] P. A. Dawson and K. D. Fitchew, "Repeater Design Requirements", British Telecommunications Engineering, Vol. 5, pp. 97-103, July 1986.

[3] S. Shibata, M. Horiguchi, S. Mitachi, and T. Manabe, "Prediction of loss minima in infrared optical fibers", Electron. Lett., pp. 775-777, 1981.

[4] B. Bendow, "Mid-IR fiber optics technology: A study and assessment," NOSC Final Report CR 243, February 1984.

[5] T. Okoshi, "Recent advances in coherent optical fiber communication systems", J. Lightwave Tech., Vol. LT-5, pp. 44-52, 1987.

[6] Grasso, G., Cheung, N.K. , et. al.,"An 11 Gbit/sec 260 km transmission experiment using a directly modulated DFB laser with two ER-doped amplifiers and clock recovery", Proc. of ECOC (Gothenburg), Postdeadline Session Paper PDA 10, 1989.

[7] K. Aida, H. Masuda, and A. Takada, "Long-span IM/DD Transmission System Experiment using High-Efficiency EDF Amplifiers", Proceedings of Optical Amplifiers Topical Meeting, Paper TuC5, pp.164-167, 6-8 August 1990.

[8] Y. K. Park, J-M P. Delavaux, R. E. Tench, and T. W. Cline, "1.7 Gb/s-419 km Transmission Experiment using a Shelf-Mounted FSK Coherent System and Packaged Fiber Amplifier Modules", Proceedings of Optical Amplifiers Topical Meeting, Paper TuC4, pp.160-163, 6-8 August 1990.

[9] K. J. Blow and N. J. Doran, "Long-distance amplified soliton systems: a novel modulation concept", IEEE Proceedings on the Optical Fiber Conference '91, Paper ThL3, 18-22 February 1991.

[10] J. J. Keller, "New AT&T System May Sharply Boost Capacity of Marine Transmission Cables", Wall Street Journal, p. B4, 2 July 1990.

[11] M. E. Kono and M. R. Brininstool, "Towards a Universal Design for ROV Telemetry via Fiber Optics", Proc. of International Telemetering Conference, Vol.14, pp. 523-535, 1983.

[12] M. Kono, M. Brininstool, and S. Cowen, "Fiber Optic Telemetry for the REGAL Torpedo", NOSC Technical Report TR 920, April 1984.

[13] M. R. Brininstool, "104-km Unrepeatered Bidirectional Fiber Optic Demonstration Link", NOSC Technical Report TR 1185, May 1987.

[14] M.R. Brininstool, S.J. Cowen, W.H. Marn, and M.C. Scallon, "Long-Distance Repeaterless Duplex Fiber-Optic Demonstration System", NOSC Technical Report TR 1411, February 1991.

[15] R. P. De Paula and E. L. Moore, "Fiber Optic Sensor Overview", Proc. of SPIE, Vol. 566, Fiber Optic and Laser Sensors III, [566-01], 1985.

[16] N. Lagakos, "Multimode optical fiber displacement sensor", Applied Optics, Vol. 20, p. 167, 1981.

[17] S. A. Kingsley, "Distributed Fiber Optic Sensors: An Overview", Proc. of SPIE, Vol. 566, Fiber Optic and Laser Sensors III, [566-68], 1985.

[18] M. R. Brininstool, "Measuring longitudinal strain in optical fibers", Optical Engineering, Vol. 26, No. 11, pp. 1112-1119, November 1987.

[19] J. T. Newmaster, M. R. Brininstool, T. Hofler, S. L. Garrett, "Remote fiber optic sensors for angular orientation", Proc. of SPIE, Vol. 838, Fiber Optic and Laser Sensors V, pp. 28-38, August 1987.

[20] J. A. Bucaro, E. F. Carome, and H. D. Dardy, "Fiber optic hydrophone", J. of Acoustic. Soc. Am., Vol.62, No. S1, pp. 1302-1304, 1977